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# EVALUATION OF 25-PERCENT ATJ FUEL BLENDS IN THE JOHN DEERE 4045HF280 ENGINE

## INTERIM REPORT
## TFLRF No. 458

by
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**Edwin A. Frame**

**U.S. Army TARDEC Fuels and Lubricants Research Facility**
**Southwest Research Institute$^{®}$ (SwRI$^{®}$)**
**San Antonio, TX**

for
**Patsy A. Muzzell**
**U.S. Army TARDEC**
**Force Projection Technologies**
**Warren, Michigan**

**Contract No. W56HZV-09-C-0100 (WD26)**

**August 2014**

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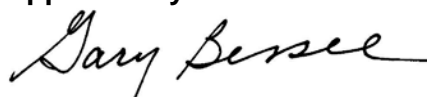for
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*Gary Bessee*

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A 25% blend of Alcohol to Jet (ATJ) and JP8 fuel was evaluated in the mechanically fuel injected John Deere 4045HF280 engine. Pre and post test full and partial load powercurves and emissions were completed, and the engine was evaluated following modified procedures outlined by the 210hr Tactical Wheeled Vehicle Cycle. The engine completed the full 210hr of testing without experiencing any unusual performance degradation related to usage of the ATJ fuel blend. All results suggest that a 25% blend of ATJ could be use in place of typical JP8 in similar applications.

**15. SUBJECT TERMS**
Alcohol to Jet (ATJ), JP8, Alternative Fuels, Stanadyne, Rotary Fuel Injection Pump, John Deere

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## EXECUTIVE SUMMARY

The objective of this test project was to determine the resulting engine performance and fuel system durability of the mechanically fuel injected John Deere 4045HF280 engine when utilizing a blend of JP8 and ATJ that maximizes the ATJ constituent while still meeting acceptance properties as defined by MIL-DTL-83133H. For this test, the ATJ constituent was found to be limited to a maximum of 25% by volume ATJ to maintain a minimum cetane value of 40. Testing was conducted following modified procedures outlined in the 210hr Tactical Wheeled Vehicle Cycle developed under CRC Report No. 406. Pre and post test full and partial load power curves and emissions were conducted to determine changes in engine and fuel system performance as a result of operating on the ATJ blended fuel.

The John Deere 4045HF280 engine successfully completed the 25% ATJ fuel blend evaluation. Results from testing showed no unacceptable performance loss or operational issues as a result of the ATJ fuel blend consumed. A primary change noted in the fuel system of the engine over the course of testing was an overall reduction in fuel flow, especially evident at the higher speed conditions. This type of pump wear can be typical in fuel lubricated rotary style systems, and despite this change the engine continued to perform and function as it should. The ATJ blend evaluated was fully additized to meet JP8 specifications called out in MIL-DTL-83133H, and in the case of the lubricity improver, was treated at the maximum allowable treat rate (24g/ml DCI-4A). Overall the ATJ blend was compatible with the 4045HF280 engine, and results from testing support the use of the 25% AJT blend in similar equipment.

# FOREWORD/ACKNOWLEDGMENTS

# TABLE OF CONTENTS

**Section**  **Page**

# LIST OF FIGURES

# LIST OF FIGURES (CONT'D)

**Figure**                                                                                                                    **Page**

# LIST OF TABLES

# ACRONYMS AND ABBREVIATIONS

ASTM – American Society for Testing and Materials

ATJ – alcohol to jet

BSFC – brake specific fuel consumption

CO – carbon monoxide

CO2 – carbon dioxide

CRC – Coordinating Research Council

DCN – derived cetane number

DOC – desert operation conditions

JP8 – jet propulsion 8

NO/NOx – nitrogen oxides

O2 - oxygen

PAWS – petroleum and water systems

TARDEC – Tank Automotive Research Development and Engineering Center

TFLRF – TARDEC Fuels and Lubricants Research Facility

SwRI – Southwest Research Institute

SOW – scope of work

THC – total hydrocarbons

TQG – tactical quiet generators

TWVC – tactical wheeled vehicle cycle

WOT – wide open throttle

# 1.0    BACKGROUND & INTRODUCTION

The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. Extensive research has been conducted in the past years to investigate alternative fuel performance, and qualify various fuels for use in military ground equipment in an effort to meet this goal. Recent investigation has focused on the viability of alcohol to jet (ATJ) based fuels produced through alcohol oligomerization, a process in which water and oxygen are removed from alcohol molecules, and hydrogen is added [1]. This report covers investigation into the use of an ATJ blended fuel in the John Deere 4045HF280 engine. This engine is representative of engines fielded in the U.S. Army's tactical quiet generators (TQG) and petroleum and water system (PAWS) equipment.

# 2.0    TEST OBJECTIVE

The objective of testing was to determine the resulting engine performance and fuel system durability of the John Deere 4045HF280 engine when utilizing a blend of JP8 and ATJ that maximizes the ATJ constituent while still meeting acceptance properties as defined by MIL-DTL-83133H.

# 3.0    TEST APPROACH

A full engine dynamometer test was utilized to evaluate the ATJ blend. Prior to the dynamometer test, engine power curves and emissions measurements were taken at ambient and desert operating conditions using JP8 and the ATJ blended fuel to map engine performance and its starting condition. The engine was then operated for 210hrs following an accelerated cycle based on the Tactical Wheeled Vehicle Cycle developed under CRC Report No. 406 [2]. After completion, engine power curves and emissions measurements were re-taken at each of the previous mentioned conditions to provide pre to post test comparison of engine operational changes across testing. All results were used to determine changes in engine and fuel system performance as a result of operating on the ATJ blended fuel. The following sections cover the technical description of the engine, discussion of the JP8 and AJT fuel blend chemical and physical properties, overview of the engine test cell installation, and an outline of the engine durability test cycle.

## 3.1    ENGINE DESCRIPTION

The engine used for the ATJ blend evaluation was the John Deere 4045HF280 (herein referred to as the 4045). The 4045 is a 4.5L inline 4-cylinder, 4-stroke, turbocharged, after-cooled, mechanically fuel injected diesel engine. The 4045 is rated at 99 horsepower at 2400 rpm and 270 lb-ft of torque at 1600 rpm using diesel fuel, and is fueled with a Stanadyne DB4 style rotary fuel injection pump and poppet injectors in a pump line nozzle configuration. Past experience has shown that rotary style fuel injection systems have potential to show increased sensitivity to fuel chemical and physical properties. This includes basic properties such as the viscosity and overall lubricity levels that impact pumping efficiency and long term hardware durability. More obscure properties such as bulk modulus can impact pressure propagation throughout the fuel injector lines in a pump line nozzle system and can artificially alter injection timing and effect engine performance.

The Stanadyne pump installed for testing was specified by John Deere for low viscosity fuel use, and came equipped with hardened internal components consistent with U.S. Army directive when using aviation distillate fuels in rotary style fuel injection systems. The fuel injection pump evaluated during testing was the Stanadyne model DB4429-6016 (John Deere part no. RE-531811, SN 16740739). All new fuel injection hardware was purchased, calibrated, and installed prior to commencing the engine testing.

## 3.2    FUEL PROPERTIES

As specified in the scope of work (SOW) for this project, the desire was to evaluate a blend of ATJ and JP8 that maximized the volume of the ATJ blending stock while still ensuring the fuel meets general property requirements set forth in MIL-DTL-83133. Since no specific tables are included in MIL-DTL-83133H for ATJ blended fuels, accepted JP8 and SPK fuel blend property specifications were referenced as practical limitations (Reference Table 1, A1, and A2 of MIL-DTL-83133). A recent supporting work directive (Contract W56HZV-09-C-0100, Work Directive 24) completed a comprehensive chemical and physical property analysis of the ATJ and JP8 base fuels for ATJ blends, as well as initial ATJ blends of 15, 35, 50, 65, and 85 percent by volume. The blend study revealed several distinct results for consideration:

- The neat ATJ fuel measured <19.4 cetane number in the ASTM D613 test, which is the lower limit of the typical low limit reference fuel

- The neat ATJ derived cetane number (DCN) by ASTM D6890 was measured at 15.65

- The measured cetane number and DCN were found to have an approximate offset of 5 points when the ATJ quantity exceeded 35% by volume

- The unusually low cetane number of the ATJ greatly reduces the resulting final blend cetane value with relatively low volumetric quantities of ATJ.

From reviewing the results of this blend study prior to testing, it was determined that the resulting cetane number of the ATJ blend fuel would be the driving limitation. The cetane number, which is the measure of the fuels ability to auto-ignite, has potential to largely impact engine combustion and performance. Per MIL-DTL-83133 Table A2, a JP8 fuel containing some component of FT-SPK (a previously approved alternative fuel), a minimum DCN of 40 is specified. Since the DCN exhibited unusual behavior in the ATJ blends, and did not demonstrate steady correlation to the true measured cetane number measured in the cetane test engine (ASTM D613), it was determined that the 40 minimum cetane limit would be applied via the D613 method for this testing. The D613 cetane value reflects the "real" cetane value of the blended fuel, as it is actually measured in an operating engine by this method.

Moving forward with this minimum established cetane value, it was found that none of the previously tested 15, 35, 50, 65, and 85 ATJ percent blends truly maximized the ATJ quantity in respect to the resulting cetane number. With the existing blend study results in-hand, a mathematical interpolation was used to predict that an ATJ quantity of 25% would yield a resulting cetane nearest the desired minimum value. An additional pilot blend was created and evaluated to confirm the predicted results, and the final cetane number for the 25% blend was measured/confirmed by D613 to be 41. This 25% blend ratio was then agreed upon between TFLRF and TARDEC to be the final blend ratio for testing the ATJ fuel.

Due to the high temperatures expected for the desert testing portion of the work, it was decided that the resulting ATJ blend would be treated at the maximum allowable treat rate (24 g/mL) of lubricity improver. The Innospec DCI-4A lubricity improver was used when producing the final blend for testing. Table 1, Table 2, and  Table 3 show the chemical and physical properties measured during WD24 of the base ATJ and JP8 fuels, as well as the "as tested" 25 percent blend ratio used in this evaluation.

**Table 1. Neat ATJ, JP8, and ATJ Fuel Blend Chemical/Physical Properties**

| Test | Method | Units | MIL-DTL-83133H Limits | SwRI Sample ID CL13-5979 Results 100% ATJ | SwRI Sample ID CL13-5980 Results JP-8 | SwRI Sample ID CL14-6189 Results 25% ATJ |
|---|---|---|---|---|---|---|
| **Water Reaction** | **D1094** | | | | | |
| Volume change of aqueous layer | | mL | - | 1.0 | 0.0 | 0.5 |
| Interface condition | | rating | 1b | 1b | 1b | 1b |
| Separation | | - | - | 2 | 2 | 2 |
| **Copper Strip Corrosion (100°C, 2 hrs)** | **D130** | rating | 1 | 1B | 1A | 1A |
| **Smoke Point** | **D1322** | mm | min 25 | 35.0 | 25.5 | 27.0 |
| **Saybolt Color** | **D156** | - | report | 28 | 29 | 27 |
| **Freeze Point (manual)** | **D2386** | °C | -47 max | <-80 | -60.0 | -57.0 |
| **Electrical Conductivity v. Temperature** | **D2624** | | | | | |
| Temperature | | °C | - | 22.2 | 21.9 | 23.9 |
| Electrical Conductivity | | pS/m | 150-700 | 0 | 1110 | 470 |
| **JFTOT-Breakpoint** | **D3241** | | | | | |
| Test Temperature | | °C | 260 | 260 | 260 | 260 |
| ASTM Code | | rating | <3 | 1 | 1 | <1 |
| Maximum mmHg | | mmHg | 25 max | 0.0 | 0.0 | 0.1 |
| **Acid Number** | **D3242** | mg KOH/g | 0.015 max | 0.007 | 0.007 | 0.008 |
| **Existent Gum** | **D381** | mg/100mL | 7 max | 10 | 1 | 2 |
| **Density** | **D4052** | | | | | |
| 15°C | | g/ml | 0.775 to 0.840 | 0.7575 | 0.7950 | 0.7857 |
| **Kinematic Viscosity** | **D445** | | | | | |
| 100°C | | cSt | - | 0.75 | 0.68 | 0.68 |
| 40°C | | cSt | - | 1.48 | 1.31 | 1.34 |
| -20°C | | cSt | 8 max | 4.82 | 4.45 | 4.50 |
| **Lubricity (BOCLE)** | **D5001** | mm | - | 0.930 | 0.660 | 0.650 |
| **Lubricity (HFRR) at 60°C** | **D6079** | µm | - | 698 | 676 | 749 |
| **Fuel System Icing Inhibitor (FSII) Content at 24°C** | **D5006** | vol % | 0.07 to 0.10 | 0.00 | 0.09 | 0.09 |
| **Particulate Contamination in Aviation Fuels** | **D5452** | | | | | |
| Total Contamination | | mg/L | 1.0 max | 0.30 | 0.30 | 0.30 |
| Total Volume Used | | mL | - | 1000 | 1000 | 1000 |
| **Distillation** | **D86** | | | | | |
| IBP | | °C | - | 174.1 | 173.6 | 173.0 |
| 5% | | °C | - | 176.8 | 183.7 | 181.5 |
| 10% | | °C | 250 max | 177.7 | 186.9 | 183.5 |
| 15% | | °C | - | 178.1 | 189.3 | 185.3 |
| 20% | | °C | - | 178.2 | 192.0 | 187.1 |
| 30% | | °C | - | 179.2 | 197.1 | 191.3 |
| 40% | | °C | - | 175.8 | 202.1 | 195.4 |
| 50% | | °C | - | 180.5 | 206.5 | 199.6 |
| 60% | | °C | - | 181.4 | 211.5 | 205.3 |
| 70% | | °C | - | 183.6 | 217.2 | 212.3 |
| 80% | | °C | - | 189.9 | 224.0 | 221.5 |
| 90% | | °C | - | 214.8 | 234.1 | 233.8 |
| 95% | | °C | - | 241.9 | 242.5 | 243.2 |
| FBP | | °C | 300 max | 259.1 | 253.5 | 254.5 |
| Residue | | % | 1.5 | 1.3 | 1.3 | 1.4 |
| Loss | | % | 1.5 | 0.6 | 0.3 | 0.5 |
| T50-T10 | | °C | - | 2.8 | 19.6 | 16.1 |
| T90-T10 | | °C | - | 37.1 | 47.2 | 50.3 |

**Table 2. Neat ATJ, JP8, and ATJ Fuel Blend Chemical/Physical Properties (Continued)**

| Test | Method | Units | | SwRI Sample ID CL13-5979 Results | SwRI Sample ID CL13-5980 Results | SwRI Sample ID CL14-6189 Results |
|---|---|---|---|---|---|---|
| | | | | 100% ATJ | JP-8 | 25% ATJ |
| Flash Point (Pensky Martin) | D93 | °C | min 38 | 44.5 | 53.5 | 51.5 |
| Cetane Index | D976 | - | - | 53.9 | 49.2 | 50.2 |
| Particle Count by APC (Cumulative) | ISO-4406 | | | | | |
| >= 4µm(c) | | class code | - | 16 | 17 | 18 |
| >= 6µm(c) | | class code | - | 15 | 15 | 16 |
| >= 14µm(c) | | class code | - | 12 | 12 | 14 |
| >= 21µm(c) | | class code | - | 11 | 10 | 14 |
| >= 38µm(c) | | class code | - | 7 | 7 | 13 |
| >= 70µm(c) | | class code | - | 0 | 0 | 13 |
| Heat of Combustion - Net Intermediate | D4809 | MJ/kg | 42.8 min | 43.60 | 43.00 | 43.18 |
| Sulfur-Mercaptan | D3227 | mass % | 0.002 max | <0.0003 | 0.0004 | 0.0003 |
| Derived Cetane Number | D6890 | | | | | |
| Ignition Delay, ID | | ms | - | 20.505 | 4.317 | 4.885 |
| Derived Cetane Number | | --- | * | 15.65 | 47.68 | 42.66 |
| Cetane Number | D613 | - | - | <19.4 | 47 | 41 |
| MSEP | D7224 | rating | - | 93 | 57 | 55 |
| Aromatic Content | D1319 | | | | | |
| Aromatics | | vol % | 25 max ** | 0.7 | 16.8 | 13.7 |
| Olefins | | vol % | | 2.3 | 2.0 | 2.1 |
| Saturates | | vol % | | 97.0 | 81.2 | 84.2 |
| Naphthalene Content | D1840 | vol% | 3.0 max | 0.0 | 0.8 | 0.5 |
| Hydrogen Content (NMR) | D3701 | mass % | 13.4 min | 15.53 | 14.20 | 14.51 |
| Sulfur Content | D4294 | ppm | 3000 max | <100 | 997 | 749 |
| * Derived Cetane Number of 40 min per table A-II, ** Aromatic minimum of 8 per table A-II | | | | | | |

**Table 3. Neat ATJ, JP8, and ATJ Fuel Blend Chemical/Physical Properties (Continued)**

| Test | Method | Units | SwRI Sample ID CL13-5979 Results | | SwRI Sample ID CL13-5980 Results | | SwRI Sample ID CL14-6189 Results | |
|------|--------|-------|----------------------------------|--|----------------------------------|--|----------------------------------|--|
| | | | 100% ATJ | | JP-8 | | 25% ATJ | |
| Speed of Sound @ 35°C | SwRI | | @ | | @ | | @ | |
| | | m/s | 184 psi | 1,175.2 | 222 psi | 1,264.8 | 413 psi | 1,247.4 |
| | | m/s | 756 psi | 1,201.9 | 832 psi | 1,294.4 | 870 psi | 1,269.4 |
| | | m/s | 1366 psi | 1,230.8 | 1977 psi | 1,326.6 | 1710 psi | 1,307.8 |
| | | m/s | 2015 psi | 1,257.3 | 2816 psi | 1,365.2 | 2473 psi | 1,329.8 |
| | | m/s | 3083 psi | 1,308.1 | 3770 psi | 1,393.1 | 3846 psi | 1,378.7 |
| | | m/s | 3808 psi | 1,329.0 | 4990 psi | 1,428.9 | 4838 psi | 1,421.4 |
| | | m/s | 4533 psi | 1,356.9 | 5944 psi | 1,453.8 | - | - |
| | | m/s | 5563 psi | 1,392.2 | -- | -- | - | - |
| Speed of Sound @ 75°C | SwRI | | @ | | @ | | @ | |
| | | m/s | 222 psi | 1,031.0 | 184 psi | 1,108.3 | 222 psi | 1,093.6 |
| | | m/s | 794 psi | 1,062.0 | 756 psi | 1,133.0 | 794 psi | 1,116.4 |
| | | m/s | 1366 psi | 1,094.7 | 1366 psi | 1,168.2 | 1519 psi | 1,151.1 |
| | | m/s | 2053 psi | 1,130.8 | 2511 psi | 1,216.2 | 2511 psi | 1,192.7 |
| | | m/s | 2740 psi | 1,157.9 | 3426 psi | 1,245.8 | 2892 psi | 1,215.1 |
| | | m/s | 3541 psi | 1,196.2 | 4571 psi | 1,290.9 | 3541 psi | 1,234.0 |
| | | m/s | 4304 psi | 1,225.2 | 5715 psi | 1,319.8 | 4609 psi | 1,281.5 |
| | | m/s | 5334 psi | 1,265.0 | -- | -- | - | - |
| Isentropic Bulk Modulus @ 35°C | SwRI | | @ | | @ | | @ | |
| | | psi | 184 psi | 149,859 | 222 psi | 180,503 | 413 psi | 173,700 |
| | | psi | 756 psi | 157,484 | 832 psi | 189,866 | 870 psi | 180,522 |
| | | psi | 1366 psi | 165,935 | 1977 psi | 200,836 | 1710 psi | 192,639 |
| | | psi | 2015 psi | 173,892 | 2816 psi | 213,736 | 2473 psi | 200,043 |
| | | psi | 3083 psi | 189,642 | 3770 psi | 223,720 | 3846 psi | 216,736 |
| | | psi | 3808 psi | 196,628 | 4990 psi | 236,804 | 4838 psi | 231,626 |
| | | psi | 4533 psi | 205,833 | 5944 psi | 246,317 | - | - |
| | | psi | 5563 psi | 217,909 | -- | -- | - | - |
| Isentropic Bulk Modulus @ 75°C | SwRI | | @ | | @ | | @ | |
| | | psi | 222 psi | 111,354 | 184 psi | 133,212 | 222 psi | 128,337 |
| | | psi | 794 psi | 118,908 | 756 psi | 139,986 | 794 psi | 134,404 |
| | | psi | 1366 psi | 127,042 | 1366 psi | 149,678 | 1519 psi | 143,772 |
| | | psi | 2053 psi | 136,374 | 2511 psi | 163,538 | 2511 psi | 155,554 |
| | | psi | 2740 psi | 143,790 | 3426 psi | 172,729 | 2892 psi | 161,877 |
| | | psi | 3541 psi | 154,372 | 4571 psi | 186,854 | 3541 psi | 167,659 |
| | | psi | 4304 psi | 162,898 | 5715 psi | 196,528 | 4609 psi | 182,077 |
| | | psi | 5334 psi | 174,815 | -- | -- | - | - |

## 3.3 ENGINE INSTALLATION & TEST CELL

The 4045 engine was purchased new for testing by TFLRF from Engines Inc, an authorized John Deere distributor. The 4045HF280 engine model was specifically called out in the scope of work for testing. Once ordered and received, the engine was prepared and instrumented for testing. The following list shows all instrumented parameters on the engine for testing:

- o Temperatures: description (data acquisition testpoint name)
  - o Coolant In (TCOOLIN)
  - o Coolant Out (TCOOLOUT)
  - o Oil Galley Temp (TOILGALLY)
  - o Oil Sump Temp (TOILSUMP)
  - o Air Before Compressor (TAIRBCOM)
  - o Air After Compressor (TAIRACOM)
  - o Air After Intercooler (TMAN)
  - o Fuel Inlet (TFUELIN)
  - o Fuel Return (TFUELRTN)
  - o Fuel Heater Loop Temp (TFHTR)
  - o Exhaust Cylinder 1, 2, 3, 4 (TEXHCYL#)
  - o T exhaust after turbo (TEXHAT)
  - o Dry Bulb (TDRYBULB)
  - o Dyno Water In (TDYNOIN)
  - o Dyno Water Out (TDYNOOUT)
  - o Day Tank Temperature (TDAYTANK)
- o Pressures: description (data acquisition testpoint name)
  - o Ambient (PAMBIENT)
  - o Pressure before compressor (PINTBC)
  - o Pressure after compressor, pre charge air cooler (PINTAC)
  - o Pressure after compressor, post charge air cooler (PMAN)
  - o Fuel pressure (low pressure side) (PFUEL)
  - o Oil galley (POILGALLY)
  - o Exhaust pressure before turbo (PEXHBT)
  - o Exhaust pressure after turbo (PEXHAT)
  - o Coolant system pressure (PCOOL)

- o Laminar flow element pressure differential (LFEdP)
- o Analog In
  - o Engine speed (SPEED)
  - o Engine Torque (TORQUE)
  - o Engine fuel consumption (FFUEL)
  - o Blow-by flowrate (FBLOWBY)

Once instrumented, the engine was installed into TFLRF Test Cell 06 for testing. The following outlines the general setup of the engine and test cell installation:

- o SwRI developed PRISM system was used for data acquisition and control.
- o The following controllers were designed into the installation to meet required operating conditions called out in the SOW:
  - o Engine speed
  - o Throttle output
  - o Coolant out temperature
  - o Fuel inlet temperature
  - o Air inlet temperature
  - o Manifold air temperature
- o The engine was coupled with a driveshaft and torsional vibration coupling to a Midwest model 1519 (eddy current) 300hp dry gap dynamometer.
- o Engine speed was controlled through dynamometer actuation, and engine load was controlled through electromechanical actuation of the fuel injection pumps throttle lever.
- o Coolant temperature was controlled using laboratory process water and a shell and tube heat exchanger. A three way process valve was used to allow coolant to bypass the heat exchanger as required to manipulate engine temperature to desired levels.
- o Inlet air was drawn in at ambient conditions through three radiator type cores plumbed prior to the engines turbocharger inlet. The radiator cores were fitted with three way process control valves and used segregated sources of hot engine coolant and chilled laboratory water to control the temperature of the incoming air charge.
- o Final intake manifold temperature (post turbocharger) was controlled through the use of an air to water intercooler and a process control valve which allowed manipulation of water supply to the intercooler core.

o Engine oil sump temperature was not controlled, and was ultimately regulated through the engine internal oil to water cooling system. Resulting oil temperature was purely a function of coolant temperature and general engine operating conditions (i.e. speed and load).

o Fuel was supplied to the engine using a recirculation tank (or "day tank") at ambient temperature and pressure conditions. The recirculation tank was connected to the engine fuel supply and return, and kept at a constant volume, controlled through a float mechanism which metered the bulk fuel supply from the test cell to replenish the tank volume. This make-up fuel flow rate was measured by a Micromotion coriolis type flowmeter to determine the engine fuel consumption.

o Fuel temperature was controlled by routing fuel leaving the recirculation tank through a liquid to liquid heat exchanger that supplied required heat transfer (in either direction) to the incoming fuel from a temperature controlled secondary process fluid. This secondary process fluid (ethylene-glycol and water mix) was heated and cooled as needed by an inline circulation heater and liquid to liquid trim heat exchanger connected to the laboratory chilled water supply.

o The engine exhaust was routed to the building's roof top exhaust handling system and discharged outside to the atmosphere. A butterfly valve was used to regulate engine exhaust backpressure as required during testing.

o Emissions were directly sampled from an exhaust probe installed between the engine and exhaust system backpressure valve. Raw emissions concentrations were measured using a Horiba MEXA-1600D Motor Exhaust Gas Analyzer, equipped with its own heated sample line and sample conditioning unit.

o Crankcase blowby gasses were ducted into a containment drum to capture any entrained oil, and then routed to the atmosphere through a hot wire flow meter to measure flow rate.

o The engine was lubricated with MIL-PRF-2104H SAE 15W40 engine oil.

o Used oil samples were collected from the engine daily to monitor engine and oil condition.

Figure 1 and Figure 2 show the 4045 engine installed in TFLRF Test Cell 06.
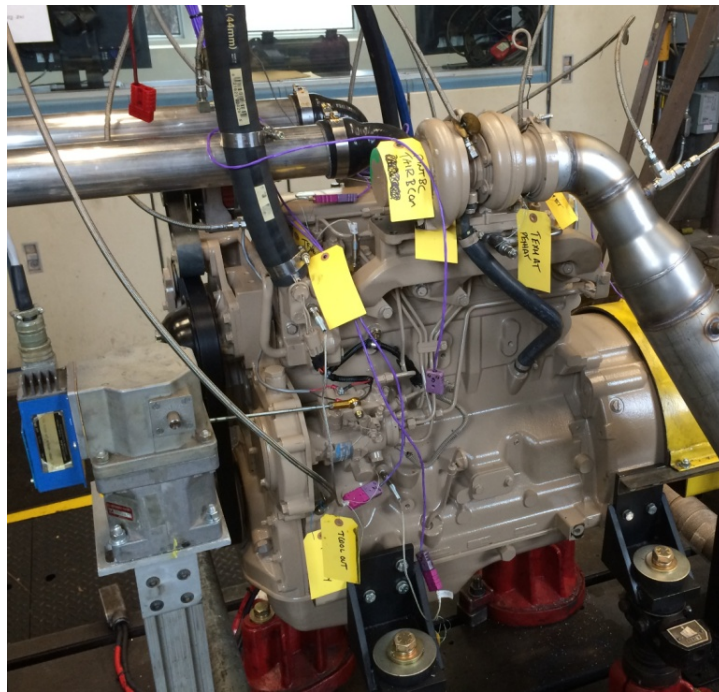


**Figure 1. John Deere 4045HF280 Installation, TFLRF Test Cell 06 – Left**
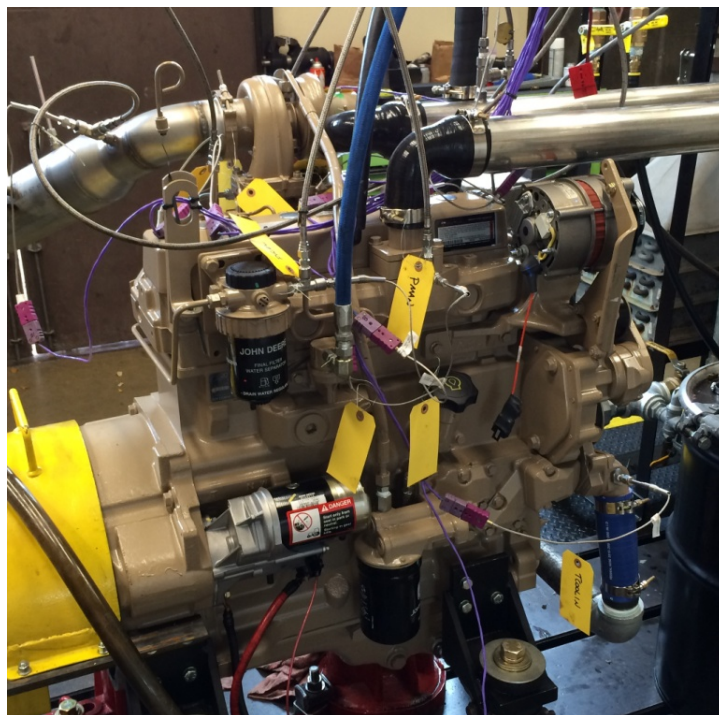


**Figure 2. John Deere 4045HF280 Installation, TFLRF Test Cell 06 – Right**

**3.4     TEST CYCLE**

The test cycle selected for the ATJ evaluation was based on the 210hr Tactical Wheeled Vehicle Cycle (TWVC) as developed in CRC Report No. 406 [2]. Modifications were made to the test cycle to accelerate the testing schedule, which consisted of a reduction of engine soak time from 10hrs to 3hrs daily, resulting in an increase of daily run time from 14hrs to 21hrs. This allows for the full 210hrs to be completed in 10 days as opposed to the original 15. The 10hr soak period in the standard TWVC was intended primarily for lubricant evaluations. This engine off soak time allows for chemical reactions to take place in the oil as part of the oil degradation process. This extended soak adds no benefit for fuels compatibility testing, thus it was reduced to accelerate the overall testing schedule.   Table 4 outlines the arrangement of daily engine operating conditions. Time adjustments were made for each step to retain the original proportion of total rated to idle hours as experienced following the standard TWVC procedure.

**Table 4. Accelerated 210hr Tactical Wheeled Vehicle Cycle**

| Cycle | Duration | Description |
|:---:|:---:|:---:|
| 1 | 2hr 10min | Rated Speed & Load |
|   | 1hr | Idle |
| 2 | 2hr 10min | Rated Speed & Load |
|   | 1hr | Idle |
| 3 | 2hr 10min | Rated Speed & Load |
|   | 1hr | Idle |
| 4 | 2hr 10min | Rated Speed & Load |
|   | 1hr | Idle |
| 5 | 2hr 10min | Rated Speed & Load |
|   | 1hr | Idle |
| 6 | 2hr 10min | Rated Speed & Load |
|   | 1hr | Idle |
| 7 | 2hr | Rated Speed & Load |
| Soak | 3hr | Engine Off |

Engine operating conditions were specified in the SOW for both ambient and desert like operating conditions (DOC). For the endurance portion of the test, all controllers followed the ambient condition setpoints as specified. For the powercurves, each fuel was operated before and after test at both operating conditions (ambient and DOC) to determine performance as a

function of fuel type, inlet temperature, and degradation as a result of testing. Some adjustments were made to the engine operating specification in the original SOW with approval from TARDEC. This included the increase in the engine coolant temperature from 205 °F to 215 °F for DOC, as John Deere engine specification data suggested a higher overall temperature capability of the engine. In addition, the fuel temperature was originally specified at 200 °F, and was then initially reduced to 145 °F after concerns that the fuel injection system was not equipped with hardened parts. Once the new correct low viscosity replacement pump with hardened parts was identified and installed, the inlet temperature was increased to 175 °F, which was more in line with previous high temperature testing of past research programs on Stanadyne pumps. Final engine operating area is shown in Table 5.

**Table 5. Engine Operating Conditions**

|  | **Ambient** | **Desert-Like Operating Conditions** |
|---|---|---|
| Inlet Air Temp | 77 ° +/- 4 °F | 120 ° +/- 4 °F |
| Fuel Inlet Temp | 86 ° +/- 4 °F | 175 ° +/- 4 °F |
| Engine Coolant Temp | 205 ° +/- 4 °F | 215 ° +/- 4 °F |
| Intake Manifold Temp | 127 ° +/- 2 °F | Range Proportional from: 118 °F +/- 3° @ idle speed 155 °F +/- 3° @ rated speed |

## 4.0    DISCUSSION AND RESULTS

The following sections review all results derived from the 25% ATJ compatibility test on the 4045 engine. This includes: pre and post test powercurves, resulting brake specific fuel consumption maps and exhaust emissions, engine operating summary from the 210hr endurance cycle, pre and post test fuel system calibration data, and used engine oil analysis.

### 4.1    PRE & POST TEST POWERCURVES

Engine powercurves were completed using both JP8 and the ATJ blend before and after testing at both ambient and desert conditions to map the engine output. This allowed direct comparison of the effect of fuel composition, inlet fuel temperature, and fuel system degradation on the engines maximum output performance. Detailed analysis of these same effects at partial loads are more adequately covered in the brake specific fuel consumption mapping and exhaust

emissions sections, but the following reviews the impact on full load performance in each scenario. Figure 3 shows an overview of the full load engine output for each fuel and temperature for pre and post test operating conditions.
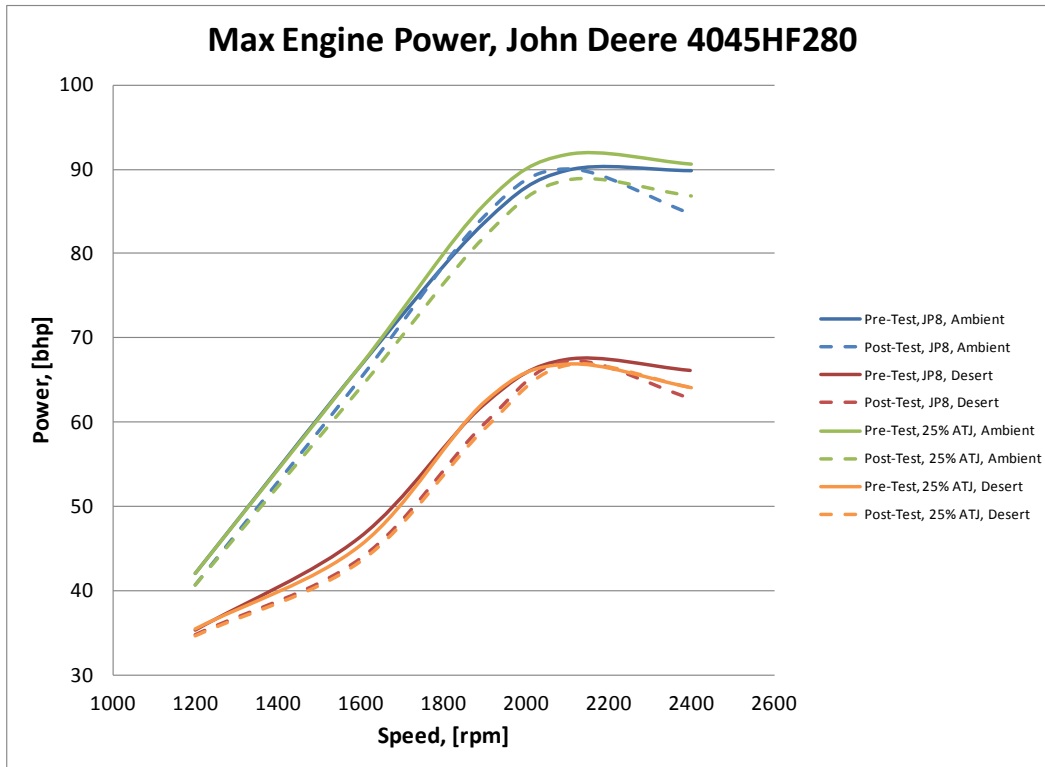


**Figure 3. Full Load Engine Output, Pre & Post Test, All Fuels**

### 4.1.1 Impact of ATJ Blend vs. JP8 on Output Performance

Figure 4 shows the engine output change between the baseline JP8 and 25% ATJ blend at both ambient and desert conditions at the start of testing. As shown, power production between the ATJ blend and JP8 at each individual temperature was found similar, with the ATJ blend actually producing equivalent to slightly increased power over the entire curve. The increased power output experienced with the ATJ blend is attributed to continued break-in of the engine over the course of the pre-test powercurves. Prior to testing the engine underwent a 50hr break-in cycle, but the pre-test powercurve data suggests that the engines efficiency continued to rise as evident by the increased power output of the ATJ blend curves that were completed after the initial JP8 curves. This power increasing break-in effect is typical for engines, and is commonly observed in dyno testing as the engine breaks into its peak efficiency.

For the pre-test curves, the most deviation was observed at the 1900rpm point for the ambient curve (2.5% increase in output for the ATJ blend), and the 2400rpm point for the desert temperature curve (3.1% decrease in output for the ATJ blend). Despite these peaks, the maximum power plots for both the ATJ blend and JP8 demonstrate nearly identical trends, and the resulting curves are collinear through a majority of the speed range. This overall consistency in power output between the two fuels is supported by similar overall energy densities of each fuel and the injected fuel flow rates recorded during testing. The similar power output between each fuel is also just as much a testament to the overall low volumetric percentage of ATJ present in the final ATJ blend than similarities between the neat ATJ and JP8 blending stocks themselves. What is important is that both fuels yield similar overall full power trends, and neither tested temperature revealed any major incompatibility between the ATJ blend and baseline JP8 at full load. This suggests that the minimum cetane value of the resulting 25% ATJ blend, at least at these loading conditions, remains fully functional in the engine without effecting its overall operation.
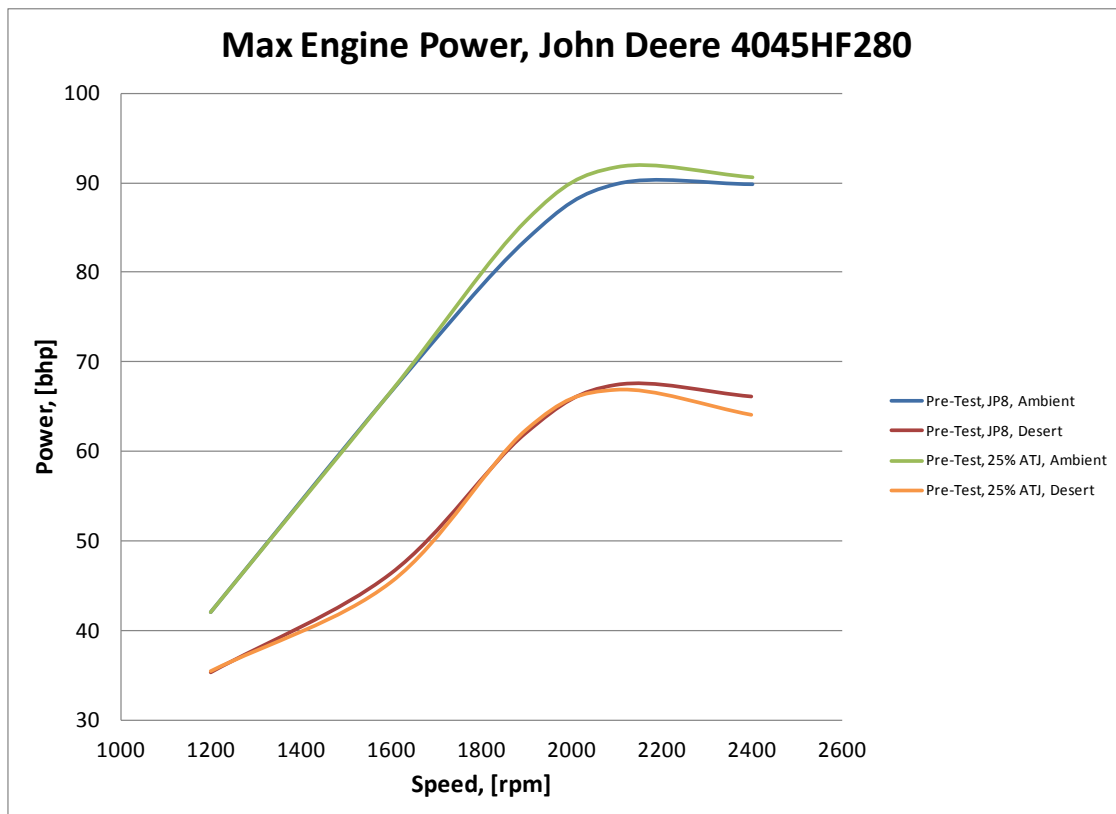


**Figure 4. Full Load Engine Output, Pre-Test, ATJ vs. JP8**

Similar to the pre test curves, the post test curves (in Figure 5) again show fairly consistent full power trends, with some additional variation in the overall power output. For the ambient temperatures, the ATJ blend curve actually peaked 2.6% higher in output power at 2400 rpm, but ranged between 1.5 to 2.9% lower in power down the engines speed range. Similar in the desert curve, the ATJ blend peaked higher by 2.2% at 2400 rpm, but ranged between a smaller 0.4 to 1.2% lower power further down the speed range. From looking at the visual trends we see that the shapes of both curves were very similar, with the ambient ATJ blend curve appearing to shift in power to a slightly higher RPM overall, while the desert curves trended similarly for both fuels throughout the entire speed range.

**Figure 5. Full Load Engine Output, Post-Test, ATJ vs. JP8**

The primary take away from the full load engine performance curves is that for both ambient and desert like temperatures, the transition from JP8 to the 25% ATJ blend showed a reasonably low impact in resulting performance. No major incompatibility was identified with the use of the ATJ

blend, and the minimum cetane value did not appear to play a large role in resulting full load performance.

### 4.1.2   Impact of Ambient Temperature on Output Performance

Although the change in power between the JP8 and the ATJ blend showed minor changes, as seen, the shift between ambient and desert temperatures showed a substantial impact on engine performance. Both fuels demonstrated a maximum power output at DOC that was less than what the engine produced at the 75% loads at ambient temperatures. Between the two fuels there was an average 27% reduction in both peak engine output power and torque when moving from ambient to DOC. This demonstrates the rotary fuel injection pump's high sensitivity to inlet fuel temperature and resulting viscosity. This sort of temperature dependence on output performance has been well documented for this style of injection system.

This overall shift in power at DOC is likely a complex result of many factors, but the largest is attributed to the reduction in fuel viscosity at temperature. Rotary style injection pumps have traditionally showed a sensitivity to low viscosity fuels even at low temperatures, and from the 86 °F ambient fuel inlet temperature to the 175 °F for the DOC, both the JP8 and the ATJ blend experience an approximate 45% reduction in kinematic viscosity (nominally 1.5x cSt at ambient to 0.8x cSt at desert). This viscosity change dramatically affects the volumetric efficiency of the fuel injection pump, directly impacting its ability to pressurize and inject fuel due to increased internal leakage in the high pressure plunger areas of the pump. As a result of the reduction in fuel flow (i.e. less energy making it to the combustion chamber), overall engine output suffers. In addition, the overall increased air temperatures for the DOC also attribute to added inefficiency of the engine. The high inlet air and manifold temperature setpoints result in a lower density air charge entering the combustion chamber during operation also contributing to the overall performance reduction of the engine.

As expected, similar trends with respect to inlet temperature were also noted between the post-test powercurves for the ATJ blend and JP8 data. Refer back to Figure 5 to see the post test powercurve plots for both the ATJ blend and JP8 curves.

### 4.1.3   Impact of 210hr TWVC on Output Performance

Lastly, some of the engine power loss before and after testing was observed purely as a result of operating the 210hr TWVC using the ATJ blend. Figure 6 shows the full load output changes for a fixed fuel (JP8) at ambient and desert conditions before and after testing. For the ambient curve, full load power in the lower speed range stayed fairly consistent between the pre and post test curves, but there was a sharp decline in output power experienced at the rated 2400rpm step (nominally 5.6% reduction). This same trend at 2400rpm was also noticed in the desert temperature curves (nominally 5.1% reduction), along with some additional low speed power deviation (ranging from 0.3 to 5.5% reduction). The drop in power at the 2400rpm for both temperatures is indicative of wear related to the injection pumps governor assembly. Depending on how and where the wear occurs, changes in the governor operation have the ability to increase or decrease overall fueling of the injection system. In this case a reduction in fuel flow at the higher speeds was realized, thus a resulting decrease in engine output power is observed. This is confirmed by the pre and post test pump calibration data (covered in detail in section 4.6) that measured a reduction of injected fuel and a resulting out-of-spec condition for the 2600 rpm and 2400 rpm (engine speed, not pump speed) operating points. The engine still produced near the same peak power before and after testing at an earlier 2100rpm step (<0.3% deviation) which could potentially make this overall change in engine output more difficult to detect by the end user of the engine. This shift in the engine power/speed relationship further suggests the governor fueling curve has changed, shifting the maximum fueling rate to lower engine speeds, and producing more of a peak power shape across a narrow speed versus the original plateau shape power trend seen pre-test.

**Figure 6. Full Load Engine Output, Pre-Test vs. Post-Test, JP8**

Figure 7 shows the same pre to post test comparison for the ATJ fuel blend. Unlike that seen in the JP8 data, overall power produced by the ATJ blend across the test duration showed greater deviation. For both temperatures, power production again trended lower at the low engine speeds (<2100rpm, nominally 2.4 to 5.2% reduction), but the rated speed and load point for DOC was not effected (<0.2% change).

**Max Engine Power, John Deere 4045HF280**

Pre-Test, 25% ATJ, Ambient
Post-Test, 25% ATJ, Ambient
Pre-Test, 25% ATJ, Desert
Post-Test, 25% ATJ, Desert
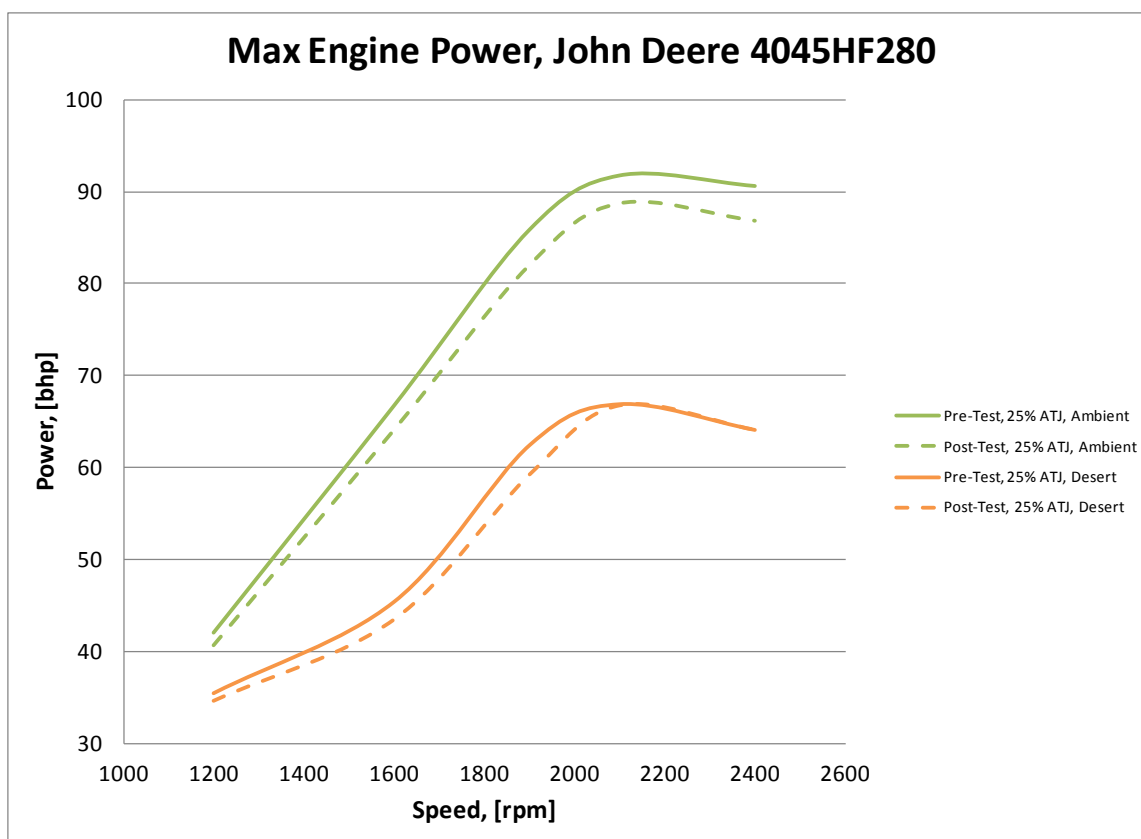
**Figure 7. Full Load Engine Output, Pre-Test vs. Post-Test, 25% ATJ**

Pump wear and fuel flow changes in these types of rotary style fuel injection system are common when operated over a long duration. This has been observed with both synthetic blends as well as traditional JP8 fuels. Overall the ATJ blend did not appear to excessively impact the performance or durability of the system, and power reductions experienced over the test duration were found to be fairly typical for rotary style fuel injection systems.

**4.2** **BRAKE SPECIFIC FUEL CONSUMPTION MAPS**

Brake specific fuel consumption (BSFC) maps were created from the partial and full load power curve data to gain a better understanding of the impact of fuel type, temperature, and pre to post test wear on the engine's performance at partial loads. When operating at light loads, differences in performance are not as evident by the resulting output shaft power, but by the fuel consumption required to produce the specified power. For example, if the engine produces 50bhp at its 50% load target with fuel A, and 50bhp at its 50% load target with fuel B, the overall output power values are virtually meaningless. What is important is the fuel flow required for each different fuel to produce the specified power. This power fuel flow relation is known as engine BSFC, which is calculated by dividing the mass fuel flow rate by the total output power [fuel consumption/power, lb/hp*hr]. Engine BSFC provides a good measure of the overall efficiency of the system, and allows better discrimination in the data sets.

Figure 8 shows the BSFC contours for JP8 at ambient temperature before and after the 210hr TWVC. Both the pre and post test maps do not yield any anomalies in the resulting BSFC, with both showing smooth transitions between all speed and load ranges, consistent with expected trends for normal operation. When closely comparing the pre and post maps to one another, it is seen that the entire map for the ambient temperature curve has shifted to a slightly higher BSFC value over the course of testing (see the decrease of purple and blue areas, and the increase in the yellow and red areas). This suggests a decrease in the engine's overall efficiency, by requiring more fuel to produce the same shaft power. The largest area of change is evident in the lower right hand corner and the upper left hand corner of the map. The lower right hand areas correspond to the high speed low load areas of the engine map. These types of operating conditions generally always demonstrate the most unstable operation in an engine map. The upper left hand areas represent the more moderate speed full load points of engine operation.
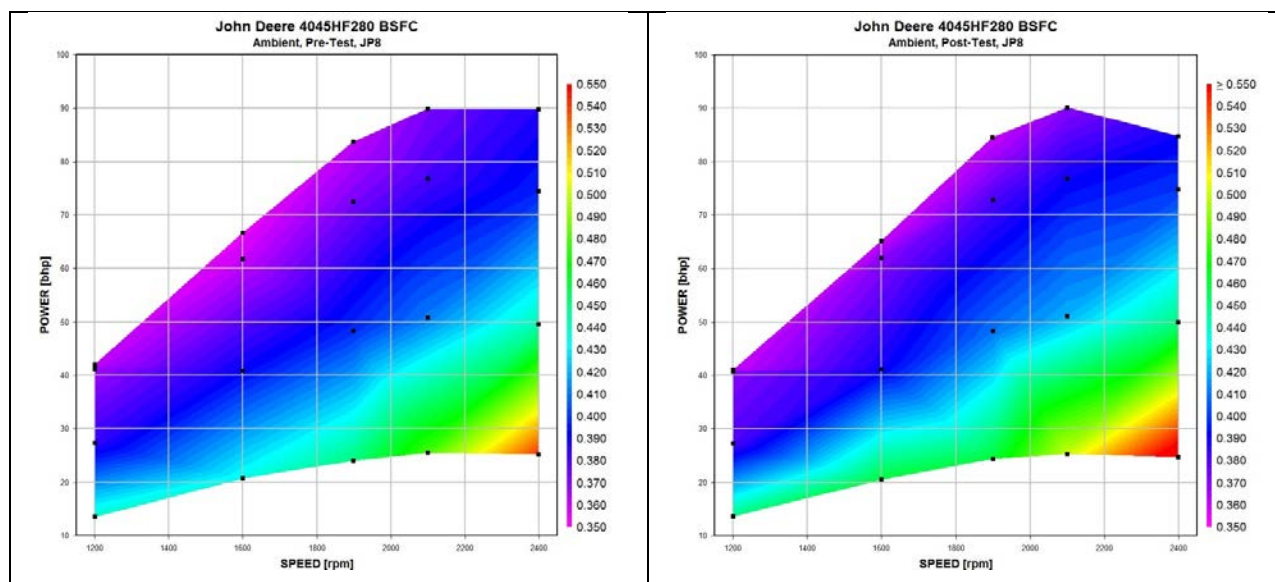
**Figure 8. BSFC Contour – Pre to Post Test, Ambient Temperature, JP8**

Figure 9 shows the same ambient BSFC maps for the ATJ blend before and after testing. Like the JP8 data, the ambient ATJ blend contours showed an overall nice consistency between BSFC ranges across the map, suggesting the ATJ blend is yielding similar and acceptable operation. Again a reduction in the low BSFC ranges is experienced in the upper left hand areas of the map across the test duration, as well as the increase in BSFC in the lower right related to the high speed low load point. This agrees with the JP8 data indicating that the overall efficiency of the engine decreased over the course of testing.
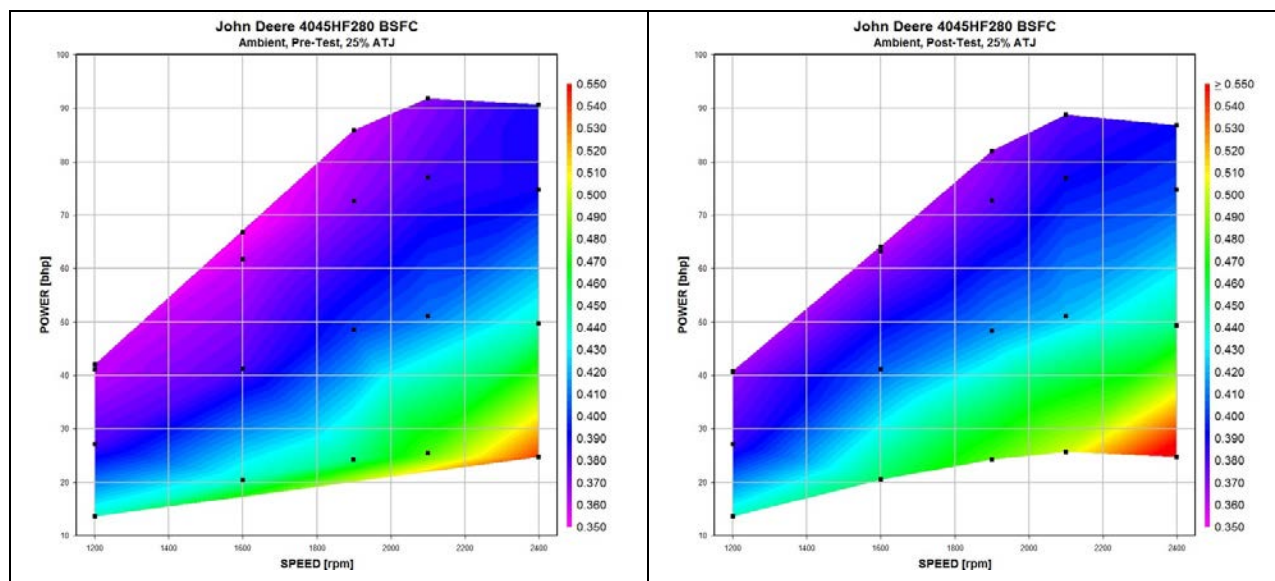


**Figure 9. BSFC Contour – Pre to Post Test, Ambient Temperature, 25% ATJ Blend**

For DOC, Figure 10 shows an even more dramatic change for JP8 before and after testing, and identifies an unusual operating condition the engine experiences at high speeds and low loads. What was seen was a sharp increase in BSFC around two mid range speeds on the 25% load curve, 1900rpm and 2100rpm. This appears to originate from a reduced power output from the engine, in which the engine dyno control system responds by increasing throttle actuation to achieve the targeted power largely affecting the resulting BSFC. In the JP8 pre-test contour (shown left) we see a slight blip in BSFC response at 1900rpm, but after 210hr test duration we see a much more prominent shift in BSFC centered around the 2100rpm operating point. This BSFC disruption was consistent with the following high temp ATJ blend data as well.
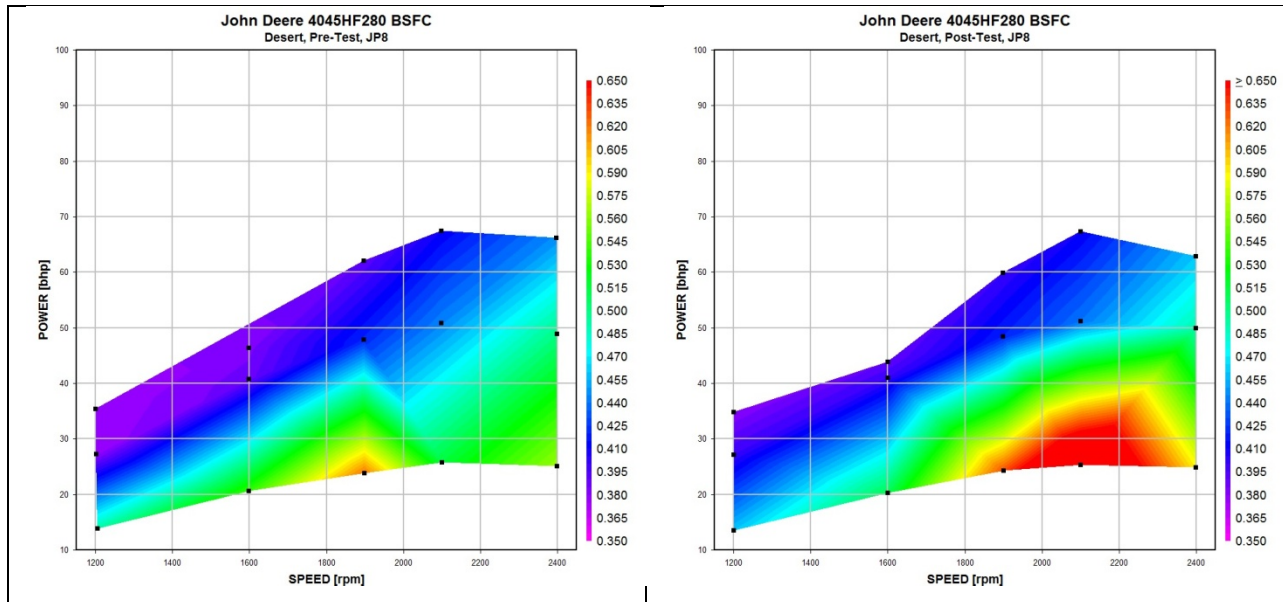


**Figure 10. BSFC Contour – Pre to Post Test, Desert Temperature, JP8**

Figure 11 shows the same pre to post test BSFC plots for the ATJ blend at desert temperatures. Both the pre and post test curves prominently show the high BSFC response centered around the 25% load 2100rpm speed point. This phenomenon was slightly more exaggerated with the ATJ blend fuel than that observed in the JP8 data, as it was more clearly pronounced in both pre and post test curves. This suggests that there is likely some fuel chemical/physical fuel property differences playing a role, but ultimately the response is being driven by the increased inlet temperatures from the DOC.
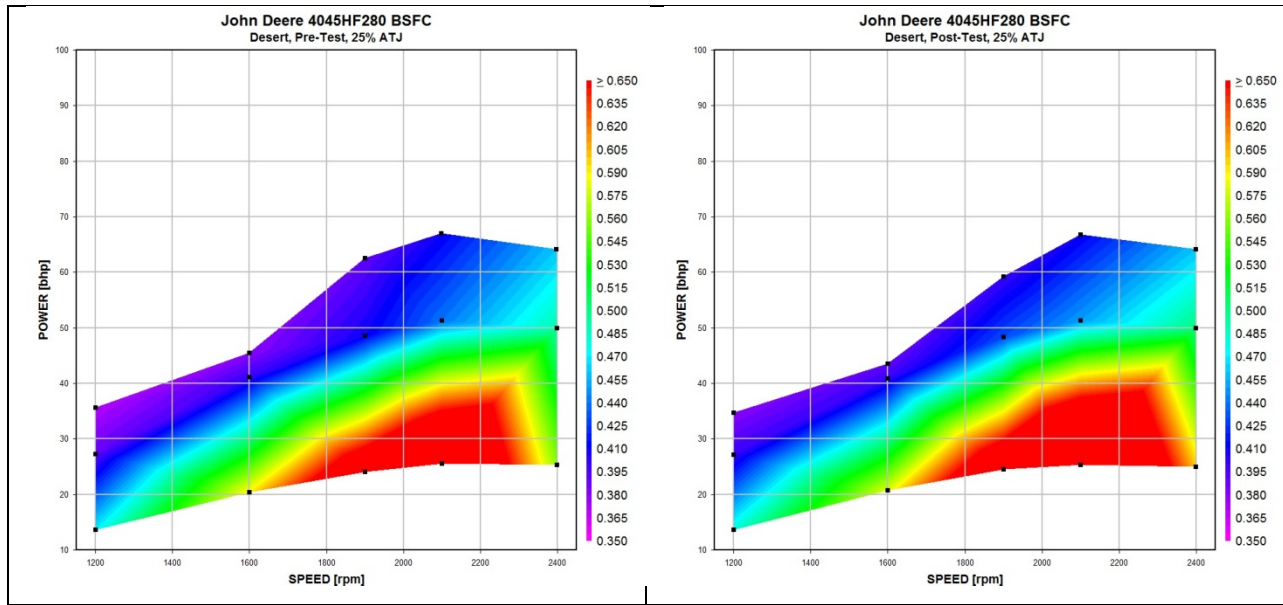
**Figure 11. BSFC Contour – Pre to Post Test, Desert Temperature, 25% ATJ Blend**

Both fuels show disturbances in the tail pipe emissions associated with these high BSFC operating points, with the severity of each relating directly to the severity of their BSFC responses. When this phenomenon occurs, significant increases in hydrocarbon (HC) and carbon monoxide (CO) emissions are present in the exhaust gas emission, as well as a corresponding reduction in nitrogen oxides (NO/NOx). This tends to indicate that combustion phasing is changing in-cylinder, resulting in an un-stable or late combustion event. This can cause an overall decrease in in-cylinder temperatures, which results in the decreased NOx emissions being observed. Further discussion of this phenomenon is presented later in the emissions discussion section of the report.

In Figure 12 and Figure 13 the plots are rearranged to compare the shift in JP8 BSFC maps from ambient to DOC before and after testing. As shown in the full load powercurve section, the reduction in power when moving to DOC is clearly visible, as is the efficiency reduction from the engine as a result of the increased temperatures.
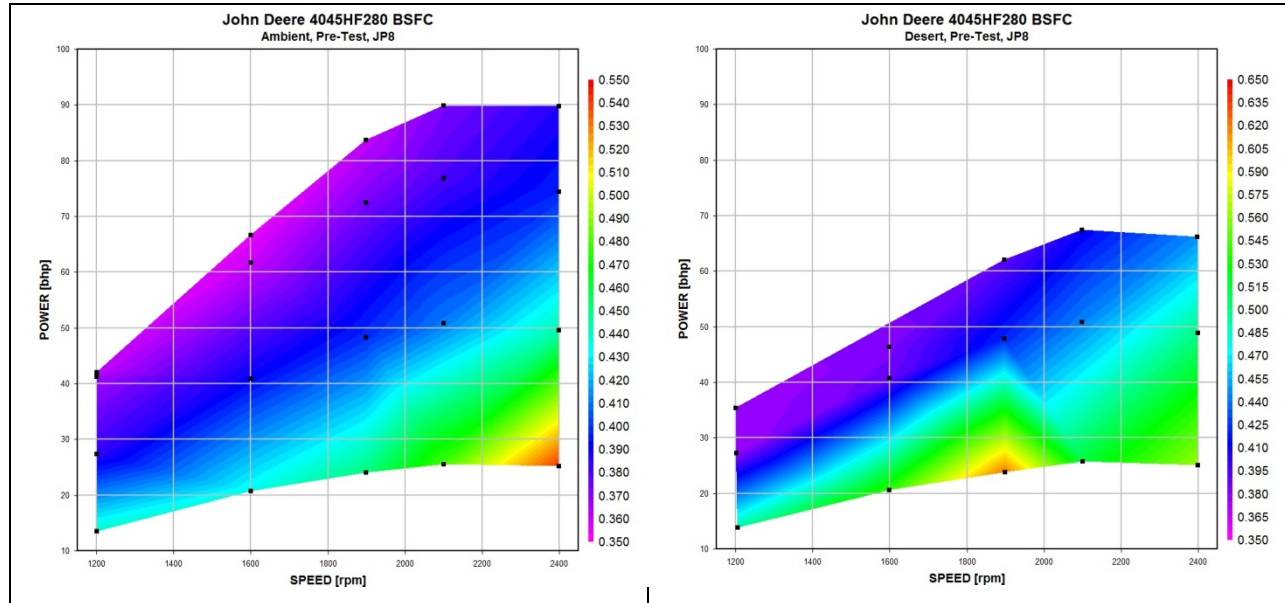


**Figure 12. BSFC Contour – Ambient to Desert Temperature, Pre-Test, JP8**
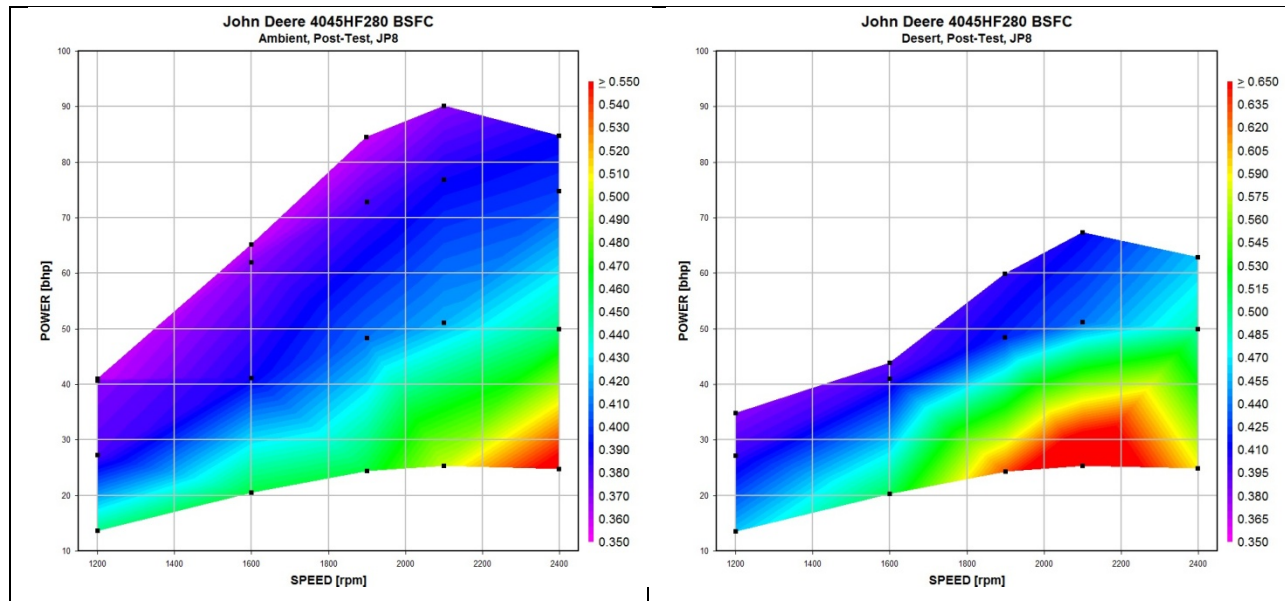


**Figure 13. BSFC Contour – Ambient to Desert Temperature, Post-Test, JP8**

Figure 14 and Figure 15 compare the shift in ATJ blend BSFC maps from ambient to DOC before and after testing. Again the reduction in power as a result of the increased temperature is most visible, along with the reduction in efficiency with increased temperatures.



**Figure 14. BSFC Contour – Ambient to Desert Temperature, Pre-Test, 25% ATJ Blend**
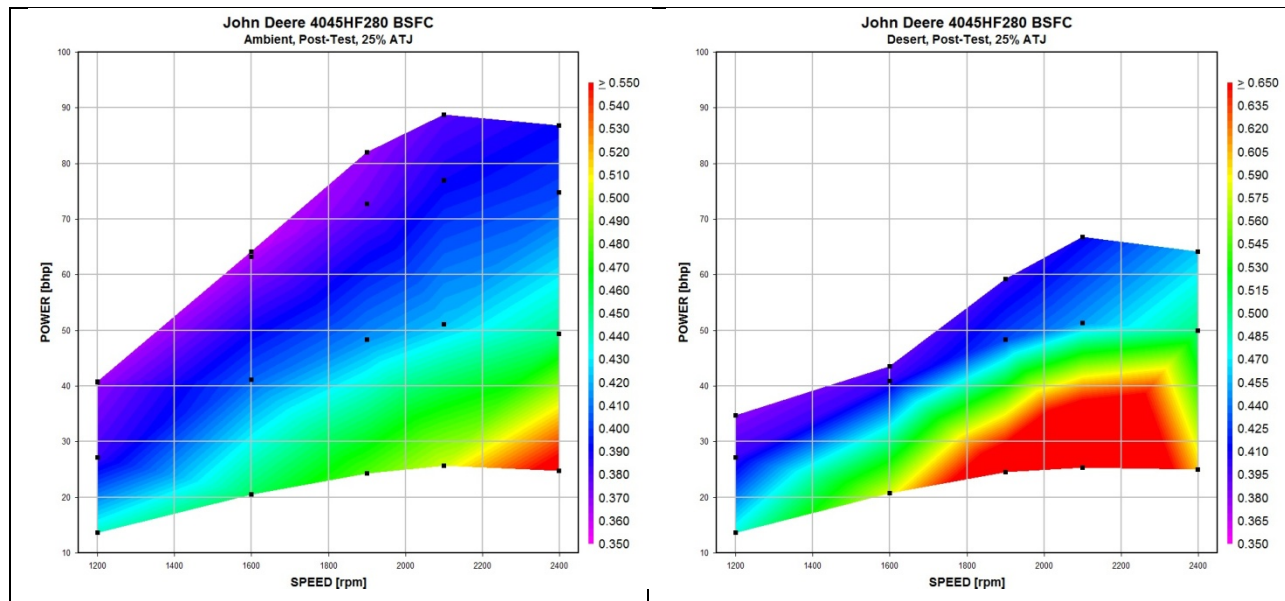


**Figure 15. BSFC Contour – Ambient to Desert Temperature, Post-Test, 25% ATJ Blend**

## 4.3 EXHAUST EMISSIONS

Exhaust tailpipe emissions were captured during the pre and post test powercurves for each fuel to help identify shifts in engine performance. Emissions sampling was completed u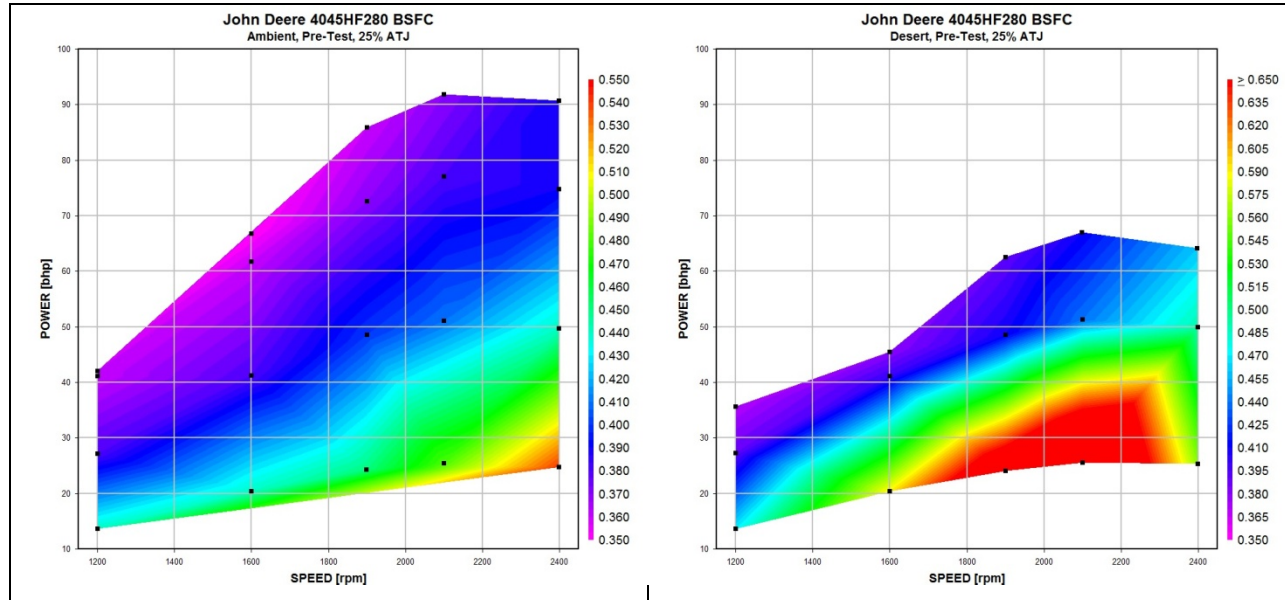sing a HORIBA 5-gas MEXA-1600 raw gas exhaust analyzer, and included measurement of carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NO/NOX), oxygen (O2), total hydrocarbons (THC). In addition, exhaust smoke number was pulled and quantified using a Bosch smoke meter. Full tabulated pre and post test emissions data for all fuels and temperatures are presented in APPENDIX A. The following will breakout and discuss the more prominent emissions (THC, NOx, & CO) for each of the pre and post test powercurves.

Figure 16 and Figure 17 show the pre-test THC emissions for each fuel and temperature. Focusing first on ambient temperature, Figure 16 shows similar THC emission trends between the JP8 and ATJ blend fuel, with the ATJ blend fuel showing only slightly higher THC concentrations at any given point, most of which is occurring at the lighter engine loads (i.e. 25% and 50%). Deviations at light load conditions are not uncommon, as in general low engine loads result in more unstable combustion events as opposed to operation at higher loads. THC increases are typically accompanied by NOx decreases, and are a result of changes in combustion phasing (in this case retarding). Emissions changes observed are thought to be a result of the more sensitive combustion at light loads, and none of the results yield any indication of incompatibility between the JP8 and ATJ blend. For the DOC however, Figure 17 shows substantial THC shifts, and backs up the previous BSFC contour data that presented the unusual operation at the light load and high temperatures. Here we can see that for both the JP8 and ATJ blend power curves, the THC response for mid speeds on the 25% load curve were very high. The emissions bench was calibrated and spanned to read within a 2000ppm range for THC, and both the JP8 and ATJ blend eclipsed this upper limit during these operational points (ALL values of the 25% curves NOT shown in the plots were above the 2000ppm span range of the instrument). Beyond this 25% load disturbance, all other load points appeared to shift to higher concentrations of THC with during DOC compared to that seen in the ambient testing.
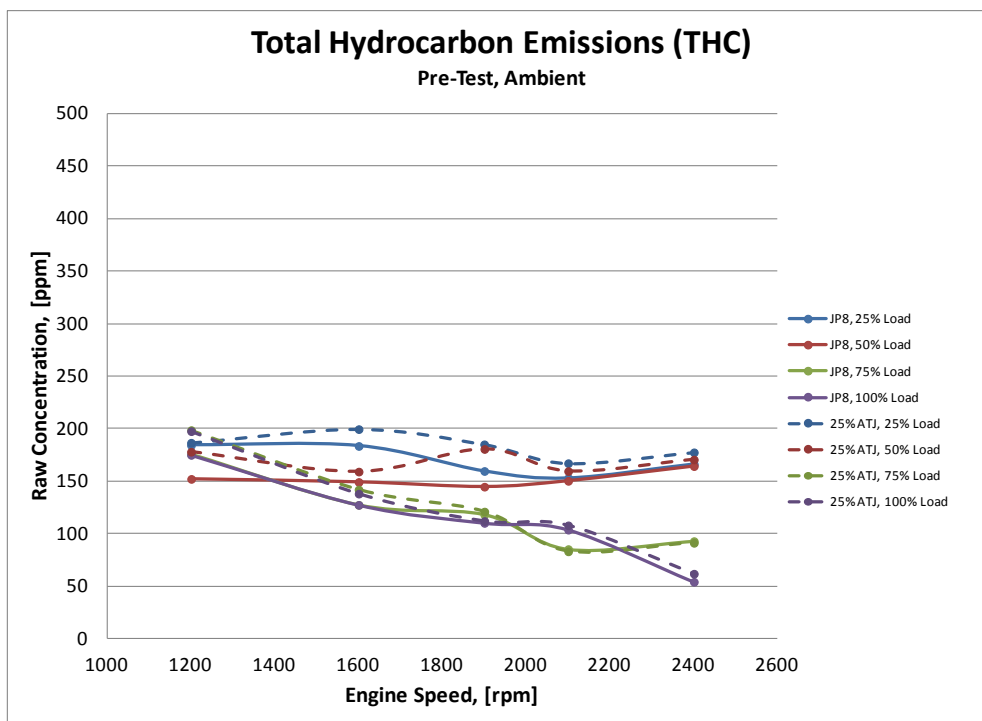
**Figure 16. THC Emissions, Pre-Test, Ambient Temperature**
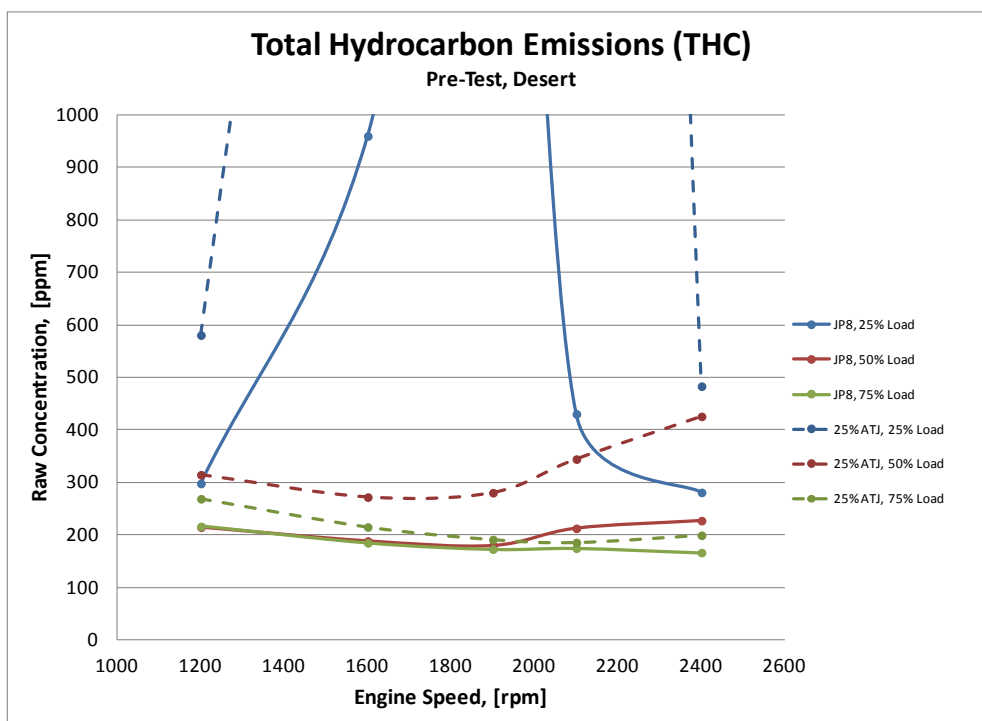


**Figure 17. THC Emissions, Pre-Test, Desert Temperature**

After studying the resulting data and reviewing the operation and control of the injection pump, this general upward shift in THC is expected with increased temperatures for both fuels. Overall injection timing of the DB4 rotary pump used by the 4045 engine is purely based on engine speed (once at operating temperature and the cold start advance is deactivated), and is a result of the balance of transfer pump pressure versus internal housing pressure (spring assisted) across the advance piston within the injection pump. The movement of the advance piston based on this pressure ratio relates to cam ring rotational movement within the injection pump advancing or retarding pump timing. With the reduced viscosity of both the JP8 and ATJ blend at DOC, more internal leakage would be expected within the pump which would result in an increase in housing pressure. With the increased housing pressure, the position of the advance piston at any given speed (which relates to the transfer pump pressure) would be retarded from the position it would equilibrate to at a lower temperature condition as a result of this changed pressure ratio across the piston. Apart from the unusual high speed 25% load response, the DOC THC response for both fuels did not reveal any dramatic differences in operation.

Figure 18 and Figure 19 show the pre-test NOx response for both fuels at both tested temperatures. As expected from the previous ambient THC data, the ambient NOx shows consistent trends between each fuel. Interestingly the NOx concentration were lower with the ATJ blend for the 75% and 100% load curves (as would be expected from the previous trends seen in the THC data), but for the 25% and 50% curves, the ATJ blend produced a slight higher NOx result. This does point to some sort of combustion interaction at light loads between the two tested fuels, but overall did not reveal any major incompatibility with the ATJ blended fuel. For the DOC, Figure 19 shows the expected corresponding dip in NOx emissions related to the THC disturbance seen previously for the 25% load curve. As well the NOx emissions for all other points were lower as a result of increased temperature, which corresponds to the timing shift discussed above. Like the THC results, apart from the 25% load points, the DOC response for both fuels did not reveal any dramatic operation differences.
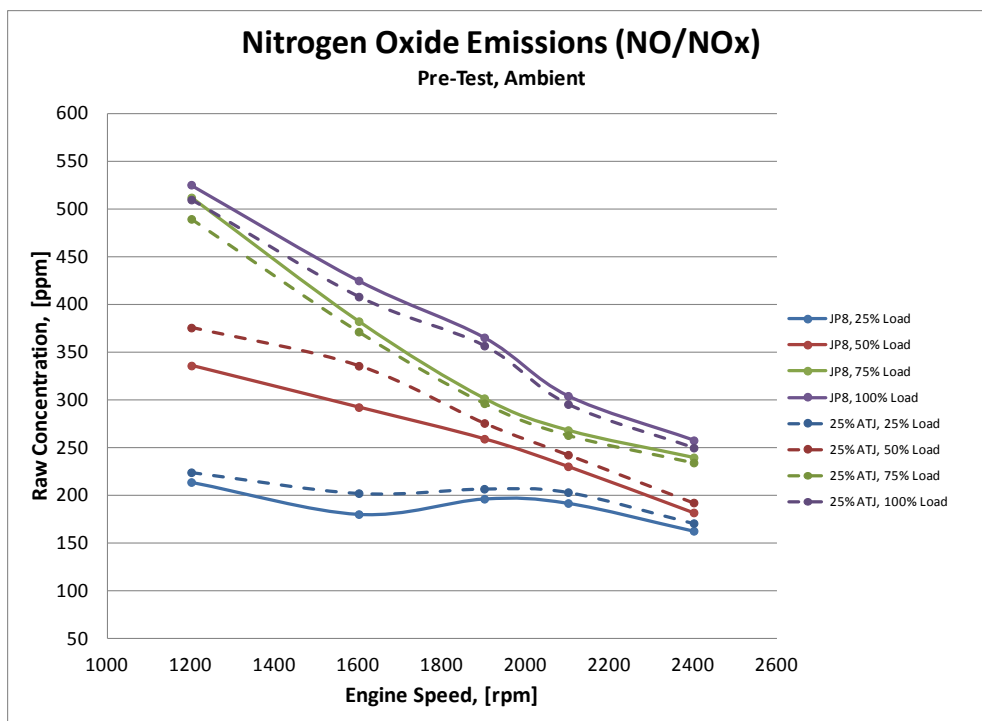
**Figure 18. NOx Emissions, Pre-Test, Ambient Temperature**
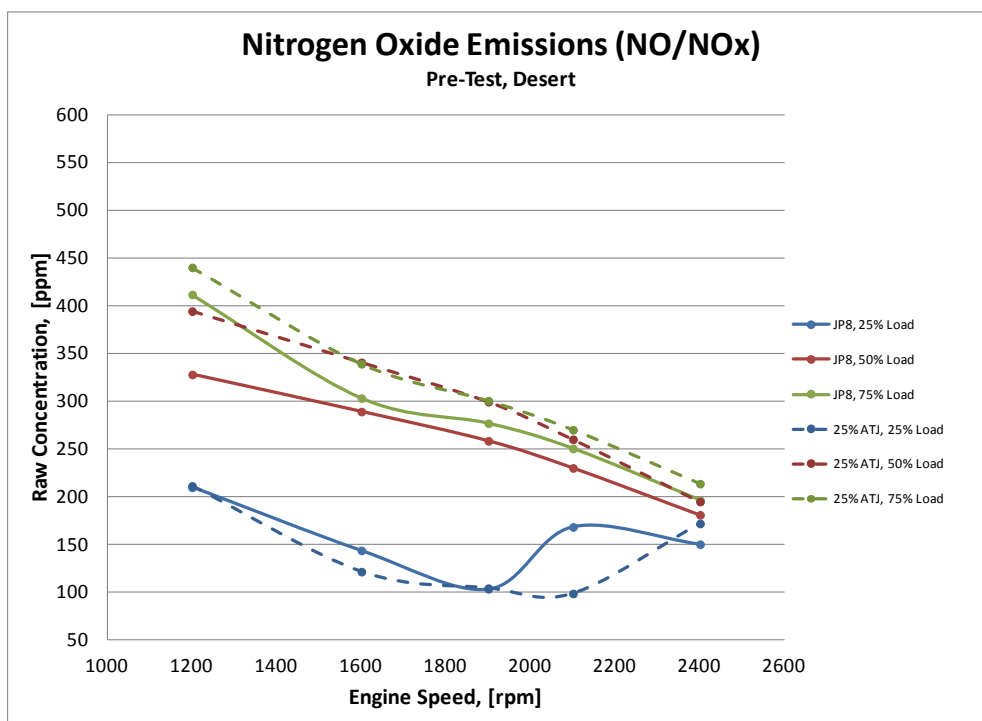


**Figure 19. NOx Emissions, Pre-Test, Desert Temperature**

Figure 20, Figure 21, and Figure 22 show the CO response for the 4045 engine. In general, CO scales directionally with the THC emissions, and inversely with the NOx emissions. As such, the trends reveal many similarities to the previously reported THC results. This includes the sharp increases noted at the high speed light loads at desert temperatures. Figure 22 shows an adjusted scale view of Figure 21, where the CO response exceeded the "normal" scale, but was still within the 3,000ppm range that the emissions bench was calibrated to measure.
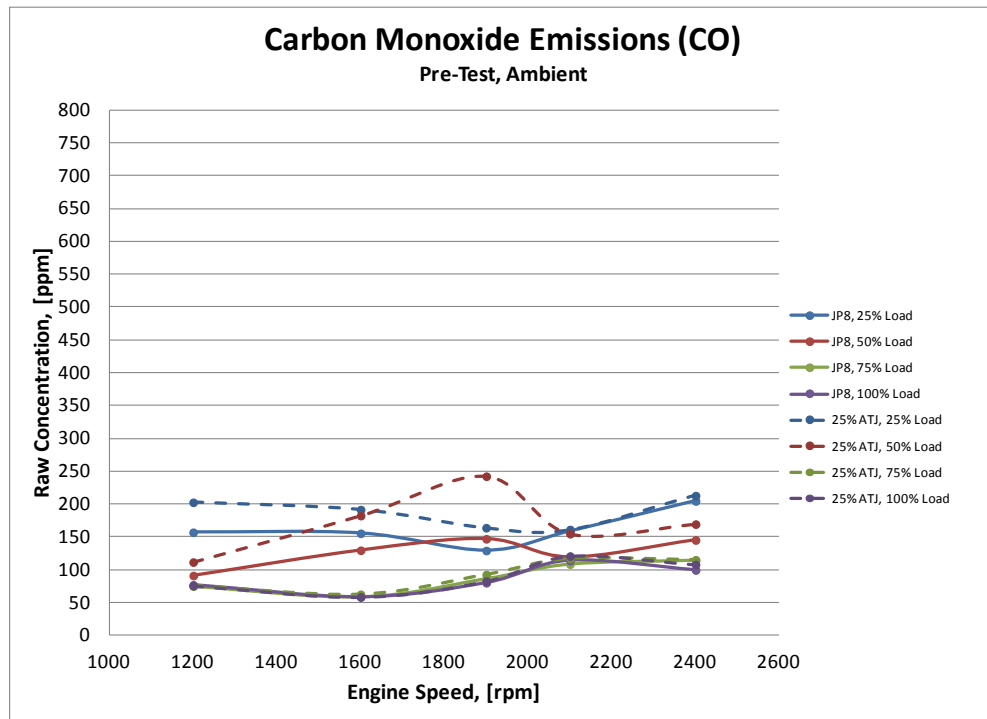


**Figure 20. CO Emissions, Pre-Test, Ambient Temperature**
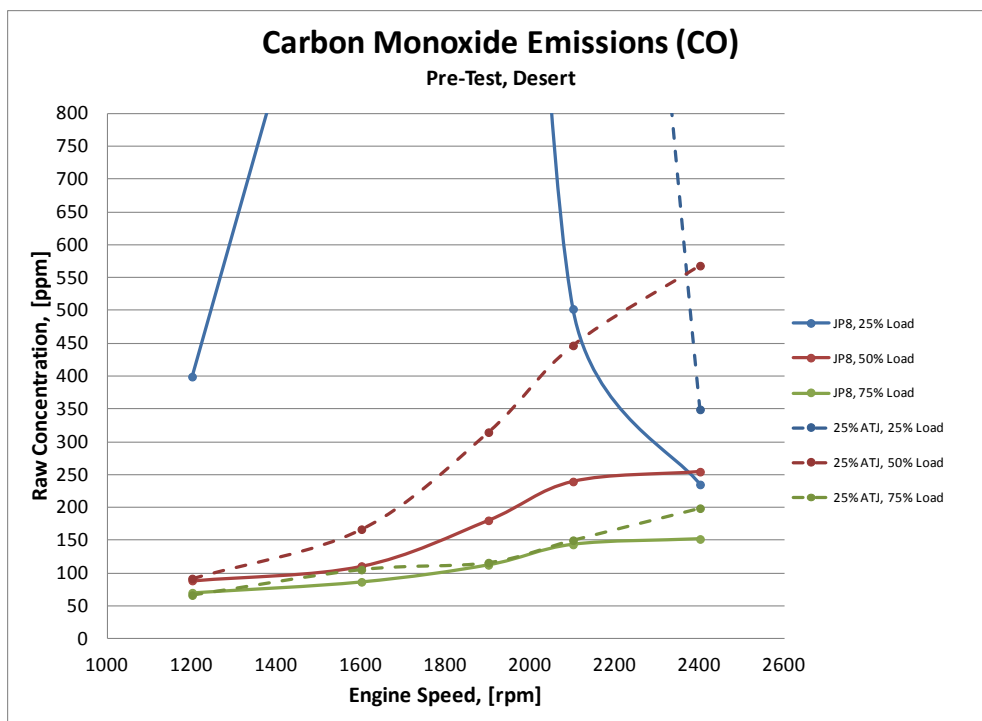
**Figure 21. CO Emissions, Pre-Test, Desert Temperature**
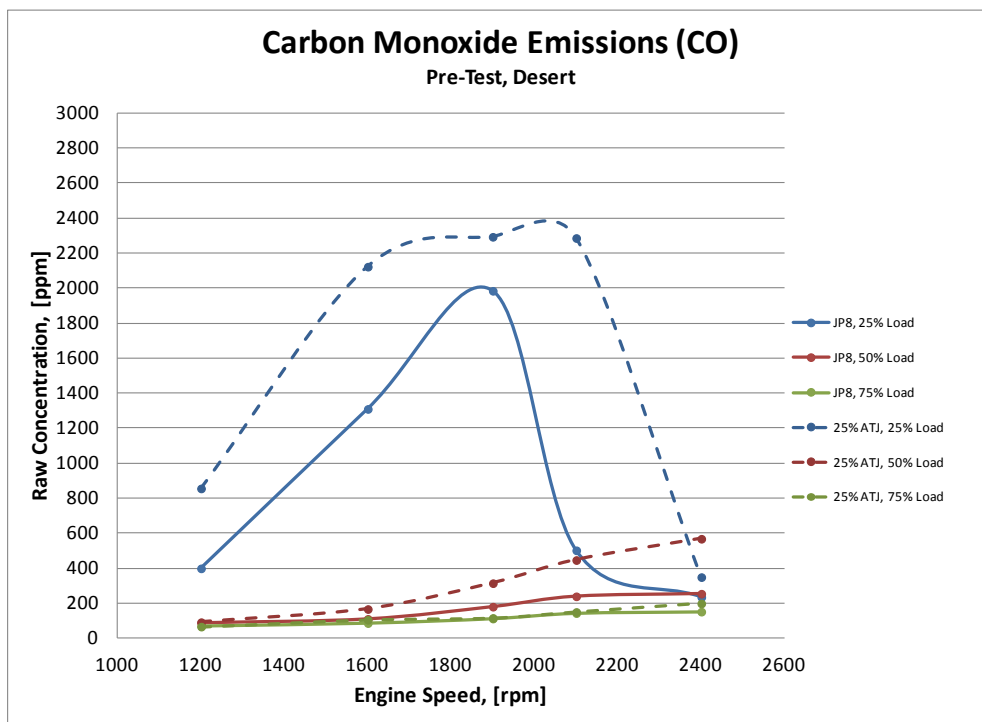


**Figure 22. CO Emissions, Pre-Test, Desert Temperature (Scaled)**

When sampling the emissions during the post test conditions, similar overall trends in comparisons to pre-test data were noted for both fuels. Figure 23 and Figure 24 show the THC response for ambient and desert conditions for both fuels. For the ambient data, THC emissions for the ATJ blend were again marginally increased over the JP8, consistent with observations from the pre-test operation. However, the post-test data showed an improvement in similarity in THC response for the two fuels when operated on the 25% load curve, with less deviation occurring between JP8 and the ATJ blend. For DOC, the unusual operation at the higher speed low load points of the 25% load curve were again observed. As a result, the THC emissions for these points substantially increase, and with the exception of the JP8 data, exceed the 2000ppm span range of the emissions bench.

Likewise, NOx emissions (shown in Figure 25 and Figure 26) remain consistent with trends observed in the pre-test data. For ambient temperature the NOx response of the ATJ blend was again lower for the 75% and 100% load points, but higher for the 25% and 50% loads. For the DOC we see the clear dip in NOx consistent with the THC increase noted for the 25% load mid-high speed operating points.
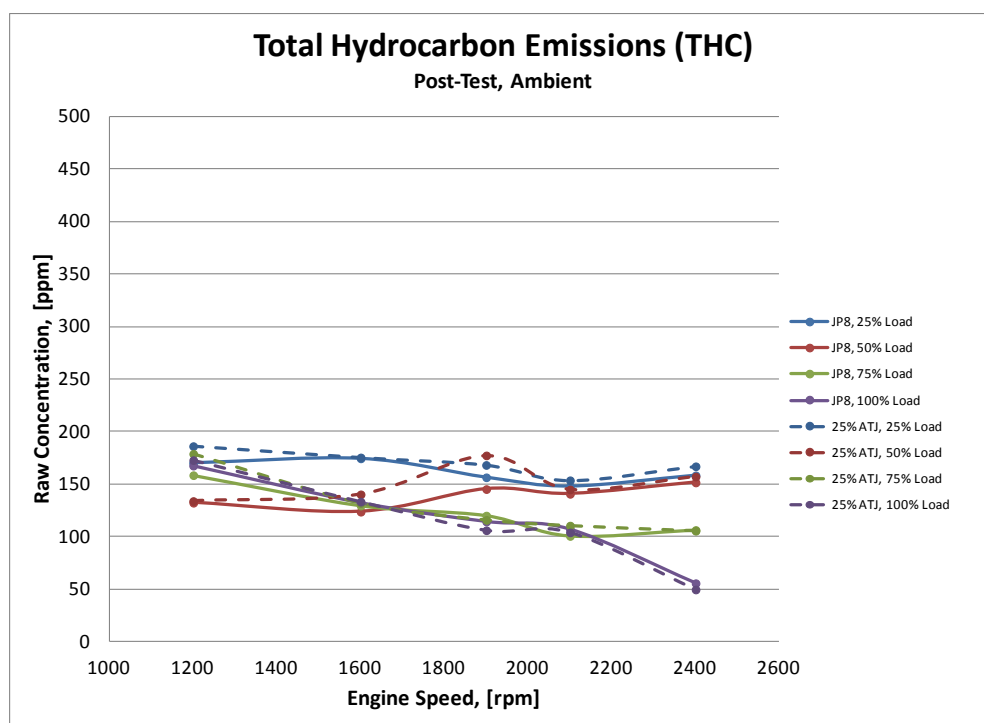


**Figure 23. THC Emissions, Post-Test, Ambient Temperature**
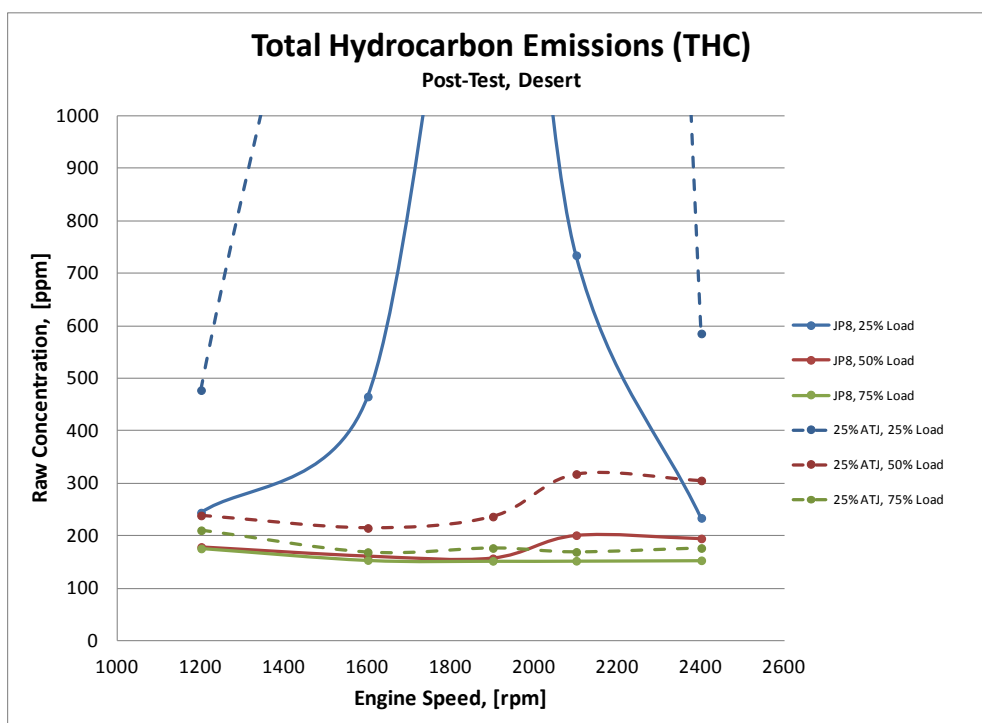
**Figure 24. THC Emissions, Post-Test, Desert Temperature**
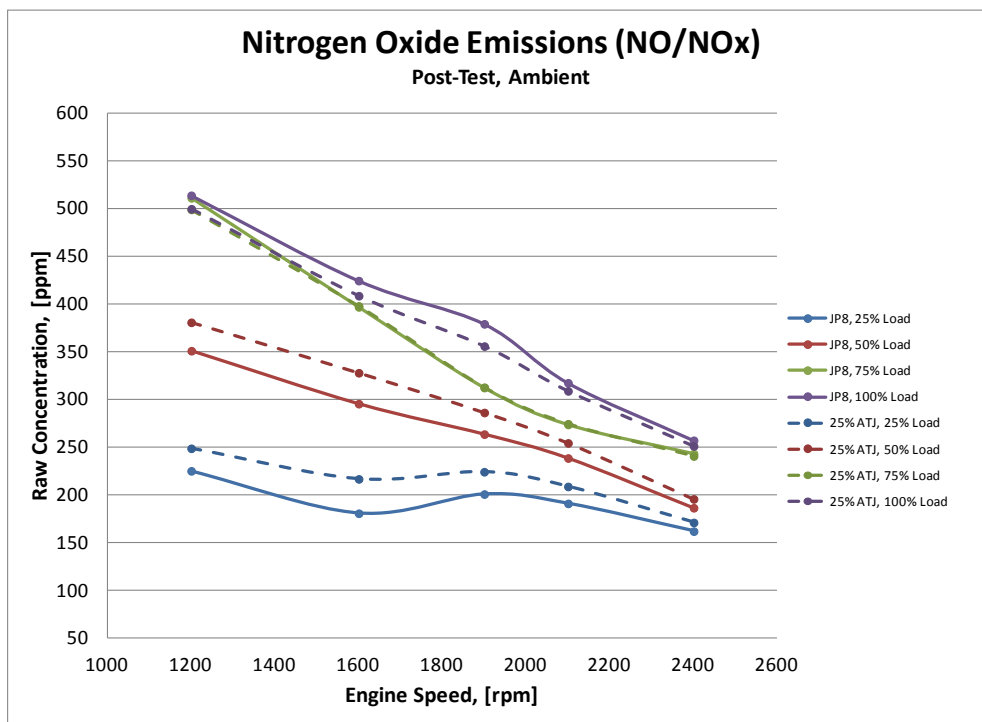


**Figure 25. NOx Emissions, Post-Test, Ambient Temperature**
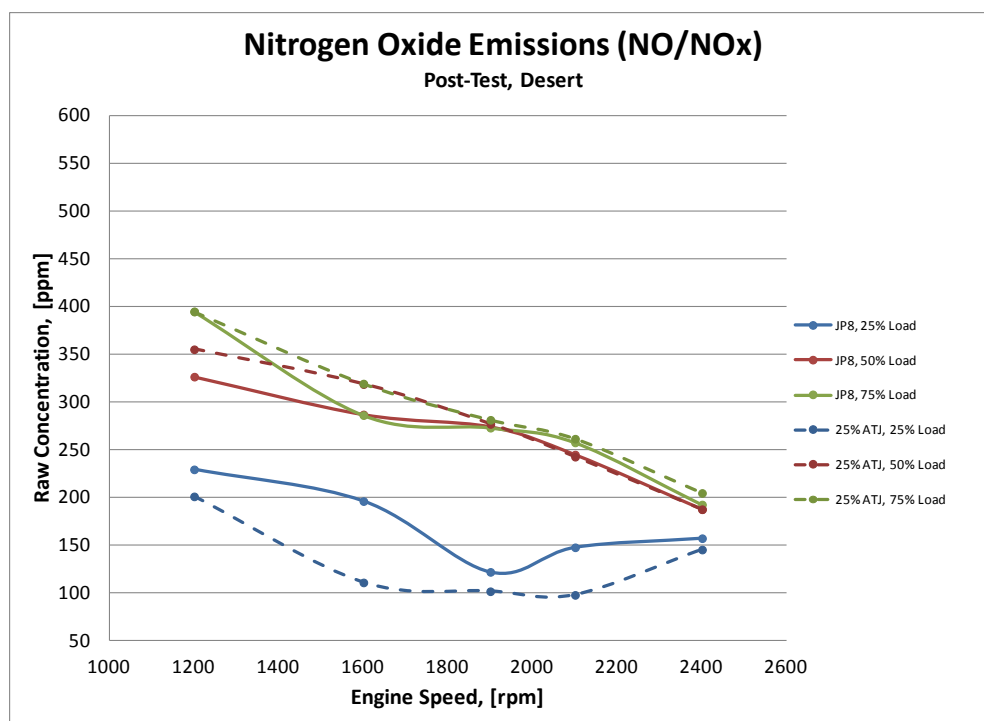
**Figure 26. NOx Emissions, Post-Test, Desert Temperature**

Figure 27, Figure 28, and Figure 29 show the CO response for the post test data. Again, overall trends were found to be nearly identical to that seen in the pre-test data, suggestion that overall the fuel system condition remained in good working order despite the long duration testing using the ATJ blend. As before, Figure 29 shows a scaled version of the plot shown in Figure 28.
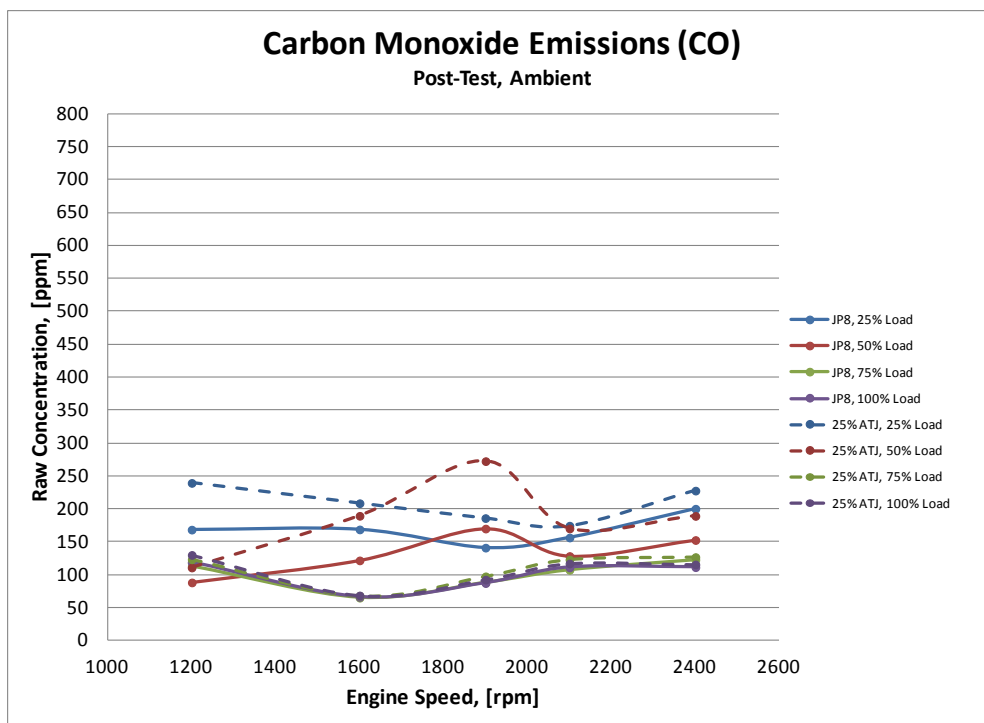
**Figure 27. CO Emissions, Post-Test, Ambient Temperature**
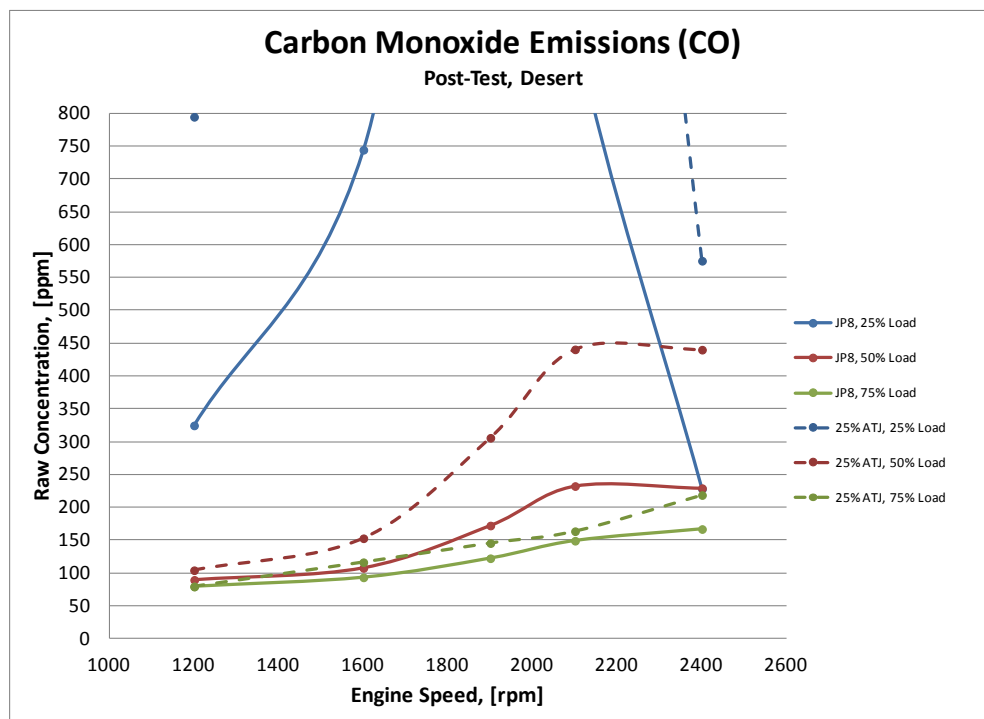


**Figure 28. CO Emissions, Post-Test, Desert Temperatures**

**Carbon Monoxide Emissions (CO)**
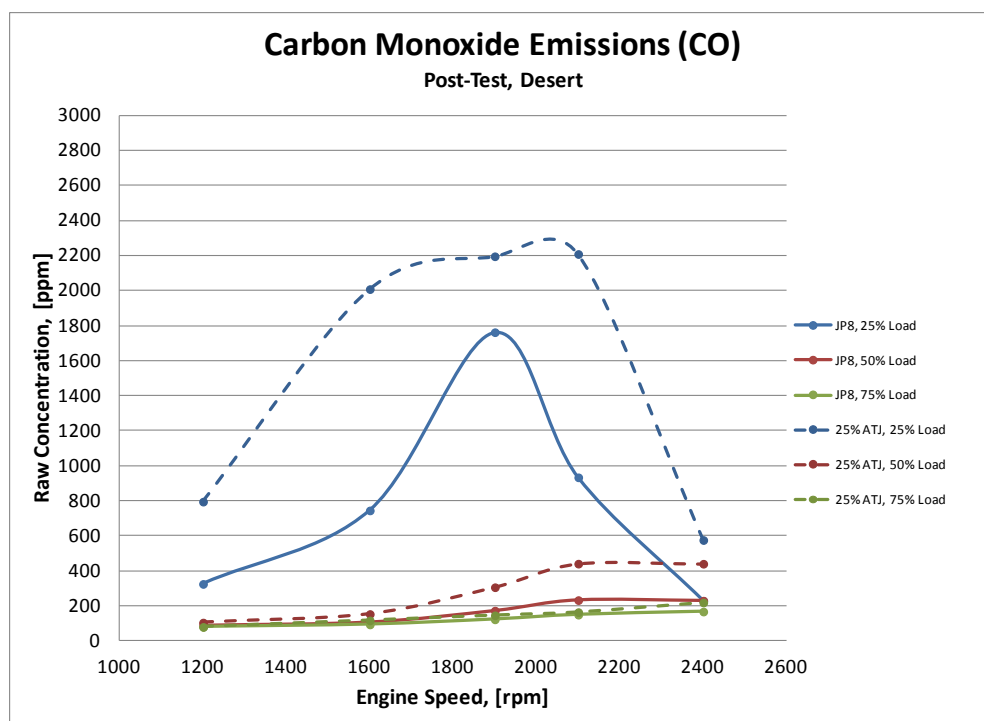
Post-Test, Desert



**Figure 29. CO Emissions, Post-Test, Desert Temperatures (Scaled)**

In terms of exhaust smoke emissions, Table 6 shows the resulting Bosch smoke number for each of the pre and post test powercurves. In general, exhaust smoke numbers were very low for both fuels, with the most smoke occurring at the highest engine load points. With the exception of a few operating points, the ATJ blend either measured equivalent or produced less smoke than the baseline JP8.

**Table 6. Exhaust Smoke Emissions**

| | PRE TEST | | | | POST TEST | | | |
|---|---|---|---|---|---|---|---|---|
| | Ambient | | Desert | | Ambient | | Desert | |
| | JP8 | 25% ATJ | JP8 | 25% ATJ | JP8 | 25% ATJ | JP8 | 25% ATJ |
| 1200_25 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 |
| 1600_25 | 0.6 | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 |
| 1900_25 | 0.8 | 0.2 | 0.0 | 0.0 | 0.8 | 0.3 | 0.0 | 0.0 |
| 2100_25 | 2.1 | 1.5 | 0.0 | 0.0 | 1.7 | 1.6 | 0.0 | 0.0 |
| 2400_25 | 2.2 | 2.0 | 0.4 | 0.0 | 2.1 | 1.5 | 0.4 | 0.0 |
| 1200_50 | 0.4 | 0.3 | 0.6 | 0.2 | 0.4 | 0.3 | 0.8 | 0.6 |
| 1600_50 | 0.3 | 0.0 | 0.4 | 0.2 | 0.5 | 0.3 | 0.6 | 0.3 |
| 1900_50 | 0.4 | 0.0 | 0.4 | 0.2 | 0.4 | 0.4 | 0.8 | 0.8 |
| 2100_50 | 0.9 | 0.2 | 0.3 | 0.2 | 0.5 | 0.4 | 0.4 | 0.2 |
| 2400_50 | 1.0 | 0.8 | 0.5 | 0.2 | 1.2 | 0.6 | 0.6 | 0.3 |
| 1200_75 | 1.5 | 1.4 | 1.2 | 1.1 | 2.6 | 2.4 | 1.5 | 1.4 |
| 1600_75 | 0.9 | 0.8 | 0.9 | 0.5 | 1.1 | 1.3 | 0.9 | 0.8 |
| 1900_75 | 0.8 | 0.9 | 1.2 | 1.2 | 1.3 | 1.3 | 1.5 | 1.1 |
| 2100_75 | 1.7 | 1.4 | 1.5 | 1.4 | 1.4 | 1.4 | 1.5 | 1.3 |
| 2400_75 | 1.8 | 1.4 | 1.2 | 0.7 | 1.7 | 1.5 | 1.0 | 0.8 |
| 1200_100 | 1.5 | 1.4 | | | 1.9 | 2.2 | | |
| 1600_100 | 1.1 | 0.8 | | | 1.5 | 1.2 | | |
| 1900_100 | 1.2 | 1.4 | | | 1.4 | 1.3 | | |
| 2100_100 | 1.7 | 1.4 | | | 1.7 | 1.4 | | |
| 2400_100 | 2.1 | 1.7 | | | 1.7 | 1.7 | | |

## 4.4   25% LOAD DESERT OPERATION & IMPACT

Several theories have been considered to provide some explanation of this observed shift in operation at high speed and low loads, but ultimately a complete solution is not immediately apparent without additional testing. The following paragraphs discuss the issue with respect to all the available data, and present the most likely area to investigate in the future to fully understand what is occurring.

Starting with the emissions, it is known that THC and CO emissions generally trend inversely with NOx emissions. The overall balance of these emissions is tightly related to the overall combustion phasing in the engine. In general, later combustion (either through later injection, or delayed ignition) decreases peak in-cylinder temperatures and results in reduced NOx emissions and increased THC (and CO) emissions. Conversely, earlier combustion typically increases in-cylinder temperatures and yields increased NOx and decreased THC (and CO) emissions. The former case (high THC, low NOx) is what was observed in the 4045 engine at the select high

speed and low load operational points at DOC. When this transition ultimately happens, the engines power output suffers, and the test cell throttle controller increases throttle output to compensate and maintain the specified power target for the commanded 25% load. This in turn increases fuel consumption, which explains the sharp increase in BSFC values at these points. Since this phenomenon appears to only occur at DOC, and happens for both the JP8 and ATJ blended fuels, it does not appear to be a strictly fuel related issue (although as alluded to earlier, the severity in differences between the ATJ blend and JP8 fuels does suggest some sort of chemical/physical fuel property interaction).

Since all results point to a change in combustion phasing, the primary question remaining is what is causing this change, and how does it ultimately relate to the increased temperatures when operating at DOC. In general there are several basic sources that can contribute to combustion phasing. This includes simple things such as physical shifts in the injection pump timing (static and dynamic adjustments), to more complex influences from the fuels chemical and physical property differences (cetane number, bulk modulus, etc). Starting with the more complex, since both the JP8 and the ATJ blend exhibited the same behavior to varying extents, a fuel chemical/physical property is most likely not the primary factor influencing the issue. Although the cetane number for the ATJ blend was targeted to achieve a minimum value, and could potentially be a large contributor the overall combustion timing, the fact that the JP8 (which measured in a typical cetane range) exhibited the same behavior preliminarily rules this out as the primary contributor. Same goes for the fuels bulk modulus. It is often theorized that bulk modulus differences change the pressure response through the fuel injector supply lines in pump line nozzle injection systems affecting resulting injector opening which changes injection timing. Again since both fuels exhibit the same behavior, any differences in the JP8 and ATJ blends bulk modulus is ruled out as the primary contributor. Both of these properties could help explain the apparent changes in severity of the phenomenon between the ATJ blend and JP8, but overall neither appear to be the root cause. Thus more focus was placed on the mechanical aspects of the engine and its fuel system to determine how they might be affected by temperature to cause this issue.

In general the 4045 engine is fully mechanically controlled. There are no "on the fly" electronic adjustments being made by an electronic engine controller causing unknown timing shift during operation, and no mechanical adjustments were made to the static injection pump timing over the course of testing. This means all powercurves attempted (for both fuels, and both temperatures) should have started from the same initial static timing condition. Since power curves were only completed after the engine was at full operating temperature, any timing changes occurring from the cold start advance mechanisms built within the pump were also ruled out. This leaves the 4045's overall injection timing to be solely a result of engine speed, and its resulting fuel transfer pump and housing pressure balance across the advance piston within the pump. As discussed previously in the report, the fuels viscosity and resulting internal leakage (which is affected by temperature) will have some impact on injection timing. In this case, a lower viscosity fuel as a result of increased temperatures should experience increased leakage rates from the high pressure plunger area of the pump and yield an increased housing pressure. This increased housing pressure compared to the unchanged transfer pump pressure would change the pressure balance across the advanced piston, and would be expected to ultimately retard the injection timing as the temperature increases. Although this does immediately fall in line with the observation of combustion phasing retard with the increased temperatures, it does not explain why the unusual operation was only observed for just a few high speed and light load points only. If this temperature viscosity effect within the pump were the primary cause of the high BSFC and emissions shift, is should have presented similar problems when running at the other operational points. All of these observations suggests that combustion phasing change is not related purely to the actual injection timing, but is more likely related to some delay or change in the combustion process after the fuel is injected into the cylinder.

With all of the above considered, it appears that with the increased temperatures during the desert testing that there is some fundamental shift in how the combustion process is occurring at these points. This change can be rationalized for the high engine speeds and light loads, as typically these sort of operating conditions yield the most inconsistent cycle to cycle combustion events, and would be expected to be the most easily impacted area of operation. The addition of the ATJ blend does seem to exacerbate the issue to some extent, which as previously mentioned does indicate that there is at least some influence from the chemical properties of the fuel on this

issue (cetane number, bulk modulus, etc). Ultimately the root cause is the increased temperature, but without high speed data acquisition and in-cylinder pressure data to quantify what is actually occurring for each combustion event, any explanation of what is occurring is purely speculative. Despite this unexplained phenomenon, the ultimate goal of this test was to determine whether or not the ATJ blend could be used in place of JP8, and in this particular case, the ATJ did not demonstrate substantially different behavior than what is observed for JP8. This supports usage of the ATJ blend.

It is debatable whether or not this phenomenon occurring in the field would even be evident to an end user of the piece of equipment. Ultimately the 4045 engine does meet the specified power and speed conditions at high temperature, but would consume more fuel at those points due to the increased required throttle position which might become noticed if operated in that regime for a long length of time (emissions changes are likely unnoticed apart from any visible smoke changes, in which the ATJ blend improved over the JP8). Depending on the final application of the engine, the amount of normal operation in this particular regime could range from frequent to potentially non-existent.

## 4.5    ENGINE OPERATING SUMMARY

Table 7 shows the 4045 engine operating summary over the course of the 210hr TWVC test duration. Per the SOW, the 210hr test duration was to be operated at the previously specified ambient testing conditions. This was assumed to only apply to the rated speed and load conditions, as the specified intake manifold temperature (post intercooler) was only applicable to an engine under load (i.e. no manifold pressure rise/heat generated at idle conditions). In addition, due to the low fuel flow and resulting low heat rejection from the engine itself at idle, it was found that the 205 °F set point for coolant temperature was not able to be maintained. As a result the controller setpoints for the idle conditions remained the same as the rated speed setpoints, but each parameter was allowed to naturally deviate and settle to their normal steady state values. This primarily affected the coolant out and manifold air setpoints only, as the inlet fuel temperature and intake air temperatures were maintained inputs to the test stand itself. For the rated condition, the four main controlled parameters (coolant out, fuel in, intake air, manifold air) are shown highlighted in the table below, along with their resulting maximum and minimum

values experienced over testing. For all setpoints except the fuel inlet temperature, all time spent at engine rated conditions were maintained within the specified deviation limits for each of the controlled processes. The fuel inlet temperature did exceed the 86 °F +/-4 °F specification briefly within the first hour of testing at rated conditions. This required a plumbing change for a fuel handling heat exchanger from laboratory processed water to chilled water to correct, and once complete fuel inlet temperature was maintained at desired levels for the remainder of testing.

**Table 7. John Deere 4045HF280, Accelerated 210hr Cycle, Engine Operating Conditions**

| Parameter: | Units: | Rated Speed Full Load Conditions Controlled @ 2400 RPM, Full Rack | | | | Idle Conditions Uncontrolled, Fixed Low Rack Position | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Avg. | Std. Dev. | Max. | Min. | Avg. | Std. Dev. | Max. | Min. |
| Engine Speed | RPM | 2400.01 | 0.74 | 2402.00 | 2397.00 | 964.45 | 24.66 | 1044.00 | 865.00 |
| Torque | ft*lb | 189.74 | 3.87 | 204.00 | 175.60 | 1.28 | 0.49 | 3.60 | -2.20 |
| Fuel Flow | lb/hr | 34.02 | 0.56 | 36.21 | 32.13 | 1.90 | 0.38 | 5.74 | -0.02 |
| Power | bhp | 86.70 | 1.77 | 93.30 | 80.20 | 0.24 | 0.09 | 0.70 | -0.40 |
| BSFC | lb/bhp*hr | 0.392 | 0.007 | 0.423 | 0.370 | - | - | - | - |
| Air Flow | ft^3/min | 286.56 | 8.10 | 310.00 | 252.00 | 60.99 | 3.90 | 75.50 | 49.50 |
| Blow-by | ft^3/min | 4.84 | 0.31 | 6.58 | 3.72 | 4.75 | 0.58 | 7.25 | 2.36 |
| **Temperatures:** | | | | | | | | | |
| Coolant In | °F | 197.88 | 1.31 | 201.30 | 194.20 | 190.52 | 6.74 | 203.90 | 170.70 |
| * Coolant Out | °F | 205.01 | 1.11 | 207.70 | 202.20 | 192.33 | 6.71 | 205.60 | 173.80 |
| Oil Sump | °F | 238.47 | 1.75 | 241.90 | 216.00 | 195.80 | 7.71 | 214.80 | 174.60 |
| * Fuel Temp In | °F | 86.00 | 0.60 | 91.10 | 83.60 | 86.05 | 3.21 | 94.50 | 79.00 |
| Fuel Temp Return | °F | 111.43 | 1.14 | 115.00 | 106.30 | 104.33 | 2.64 | 112.30 | 95.10 |
| * Air Before Compressor | °F | 76.99 | 0.73 | 80.60 | 73.30 | 76.85 | 1.51 | 83.50 | 72.60 |
| Air After Compressor | °F | 234.64 | 2.28 | 246.80 | 226.30 | 89.68 | 1.82 | 102.50 | 83.80 |
| * Air After Cooler | °F | 127.01 | 0.43 | 128.60 | 125.40 | 93.37 | 3.31 | 111.00 | 84.70 |
| EGT Cylinder 1 | °F | 853.40 | 4.95 | 871.20 | 835.10 | 263.50 | 5.76 | 325.90 | 247.40 |
| EGT Cylinder 2 | °F | 898.82 | 5.24 | 926.20 | 879.40 | 253.83 | 5.70 | 330.90 | 241.10 |
| EGT Cylinder 3 | °F | 900.49 | 6.01 | 933.30 | 885.00 | 266.40 | 6.04 | 342.10 | 252.50 |
| EGT Cylinder 4 | °F | 890.58 | 4.82 | 921.70 | 874.50 | 267.51 | 7.11 | 332.40 | 242.50 |
| EGT After Turbo | °F | 817.84 | 7.65 | 867.80 | 792.50 | 253.85 | 10.64 | 422.80 | 236.90 |
| Test Cell Dry Bulb | °F | 88.57 | 5.29 | 101.10 | 77.50 | 86.82 | 4.86 | 98.60 | 78.00 |
| **Pressures:** | | | | | | | | | |
| Oil Galley | psig | 58.54 | 0.44 | 63.20 | 57.80 | 45.43 | 1.07 | 47.90 | 42.30 |
| Fuel Supply Pressure | psig | 3.15 | 0.94 | 4.30 | 0.50 | 3.81 | 1.47 | 7.60 | 2.30 |
| Ambient Pressure | psiA | 14.30 | 0.02 | 14.36 | 14.25 | 14.30 | 0.02 | 14.37 | 14.25 |
| Intake Before Compressor | psiA | 13.98 | 0.02 | 14.04 | 13.92 | 14.23 | 0.02 | 14.29 | 14.18 |
| Intake Depression (Calc) | psig | 0.32 | 0.01 | 0.34 | 0.30 | 0.07 | 0.01 | 0.10 | 0.06 |
| Intake After Compressor | psig | 12.86 | 0.23 | 13.96 | 12.10 | 0.03 | 0.04 | 0.15 | -0.08 |
| Intake After Cooler | psig | 12.33 | 0.24 | 13.50 | 11.60 | -0.20 | 0.06 | -0.10 | -0.30 |
| Exhaust Before Turbo | psig | 8.27 | 1.56 | 10.33 | 3.02 | 0.51 | 0.10 | 0.84 | -0.04 |
| Exhaust After Turbo | psig | 0.18 | 0.02 | 0.40 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 |
| Coolant System | psig | 8.48 | 0.92 | 10.34 | 4.71 | 6.69 | 0.84 | 9.12 | 4.72 |

*Denotes items controlled at rated speed, does not apply to idle conditions*

Engine operating conditions specified at +/- 4°F for inlet air, fuel, and engine coolant out temperature. Intake manifold temp specified at +/-2°F. All parameters within spec throughout entire test with the exception of 2 minutes at >90°F fuel inlet temp at start of test. As a result the fuel conditioning system adjusted from process water to chilled water to maintain desired fuel inlet temperature. No other excursions outside of desired test conditions were recorded.

Temperature controllers remained at rated speed target set points during idle operation steps, but engine allowed to naturally deviate and reach its own steady state temperatures.

## 4.6     FUEL SYSTEM CALIBRATION & PHOTOGRAPHS

Table 8 shows the pre and post test calibration data for the Stanadyne pump used by the 4045 engine for the ATJ evaluation. The pump underwent a full pre-test calibration procedure to document and set starting conditions, and verify that all parameters produced from the injection pump where within specification. After the completion of testing the pump again underwent a calibration review process where the pump was run to document any shift in the output parameters as a result of testing. Consistent with what was seen in the pre and post test powercurve data, the primary change observed was a reduction in fuel flow at various speeds (note, pump speed is exactly half engine speed). For the rated 2400 rpm engine speed (1200 rpm pump speed), we see a reduction in wide open throttle (WOT) fuel flow, supporting the reduced power at the 2400 rpm points in the post test powercurves. We also see a significant increase in return fuel flow at this condition, which suggests that more leakage is occurring in the high pressure plunger area of the pump and causing additional fuel to vent from the housing. Governor action at the high speeds could also be contributing to the increased return flow, as the balance of pressures within the pump would be disrupted by the reduced fueling and pressure regulating action of the transfer pump. Low idle fuel delivery was also reduced, and was noted during test operation as a progressively lower idle speed from the engine from its starting condition. Despite this, WOT cranking fuel delivery remained above the low limit, suggesting that the engine would not be expected to have any starting issues. This was supported by easy starting throughout testing.

**Table 8. Fuel Injection Pump Calibration Data, Pre & Post Test**

# Stanadyne Pump Calibration / Evaluation

| Pump Type : DB4426-6018 | Inj Pump SN: 16740739 |
|---|---|
| Test Fuel : 25% ATJ - 75% JP8 | |

| PUMP RPM | Description | Spec. | Before | After | Change |
|---|---|---|---|---|---|
| 1325 | WOT - Gov. Cutoff | 5cc Max | 0 | 0 | 0 |
| 1300 | WOT - Gov. Cutback | 10-12cc | 12 | 8 | 4 |
| | Advance | 11-12 deg. | 11 | 11.64 | 0.64 |
| 1200 | WOT Sol. De-energized | 4cc Max | 0 | 0 | 0 |
| | WOT Torque Screw Del. | 83.5-84.5cc (adv. 2-3deg) | 84 (2.5) | 80 (2.3) | 2 |
| | Adj. Throttle position | 50-60cc (see note, advance)* | 60 (2.75) | 60 (3.16) | 0 |
| | Adj. T. pos. Lt. Load Adv. | 39.5-40.5cc (adv. 5.5-6.5deg) | 40 (6.0) | 40 (6.0) | 0 |
| | Return Fuel | 400-700 cc/minute | 500 | 800 | 300 |
| 850 | WOT Fuel Delivery | 94-95cc | 95 | 90 | 5 |
| 800 | WOT Transfer pump psi | 76-78psi (Adv. 0-.3deg) | 78 (0) | 76 (0.04) | 2 |
| | ADJ Throttle position | 67-68cc (Adv.0-.3deg) | 68 (0) | 68 (0) | 0 |
| | Adj. T. pos. Lt. Load Adv. | 44.5-45.5 (Adv 2.5-4.0deg) | 45 (2.5) | 45 (1.69) | 0 |
| 700 | WOT Fuel Delivery | 90-91cc | 91 | 85 | 6 |
| 500 | WOT Fuel Delivery | 73-83cc | 78 | 76 | 2 |
| 450 | WOT Fuel Delivery | 79.5-80.5cc | 80 | 80 | 0 |
| 425 | Low Idle Fuel Delivery | 13-15cc (Adv. 2deg. Min.) | 14 (2.25) | 4 (3.75) | 10 |
| 200 | WOT Sol. De-energized | 4 cc max. | 0 | 0 | 0 |
| | Vacuum | 18"HG | 18 | 18 | 0 |
| 75 | WOT Cranking Delevery | 35cc min. | 76 | 82 | 6 |
| | Transfer pump psi. | 10 psi min. | 22 | 18 | 4 |
| 250 | WOT Cold Adv. Sol. Engz | .5max Advance | 0 | 0 | 0 |
| 800 | ADJ Cold Adv. Sol. Engzo | 48-52cc (Adv 6.5-7.5deg) | 50 (6.75) | 50 (7.0) | 0 |
| | Air Timing | Record | | 197° | |
| | Fluid Temp. Deg. C | | 44 | 44 | |
| | Date | | 3/26/2014 | 7/7/2014 | |

**Notes :**   *Reading to be no greater than reading obtained at 800rpm light load setting.

Table 9 shows the individual fuel injector checks before and after testing. Overall the opening pressure dropped slightly over the course of the test, which is a normally expected result. All pressures remained relatively consistent, with no injector exhibiting any unusual pressure behavior or tip leakage.

Figure 30 shows the individual fuel injector tip photos before and after testing. The pre-test photos (shown left) were photographed as received from John Deere without experiencing any installation or run time within the engine. This explains the completely clean tip surfaces. The post-test photos (shown right) were taken as removed from the engine after the completion of testing, prior to undergoing the post test fuel injector checks to avoid disturbing any deposits. Overall deposit levels are considered normal. All fuel injector holes were open and clear, and overall tip deposit levels were not considered excessive. The white colored areas that show in the post-test photos (primarily on injector number 3) are exaggerated reflections from moisture present on the injector tip during photographing. This coloration is indistinguishable to the naked eye, and is not attributed to any sort of ash deposit on the tip of the injector.

## Table 9. Fuel Injector Operation Check, Pre and Post Test

**Stanadyne Rotary Pump Lubricity Evaluation**
JD 4045HF280 Fuel Injector Test Inspection

| Test No. | Inj. Pump ID No. | Fuel | Inj. ID No. | Opening Pressure (pre-test) | Opening Pressure (post-test) | Tip Leakage (pre/post) | Tip Leakage (post-test) | Chatter (pre-test) | Chatter (post-test) | Spray pattern (pre-test) | Spray pattern (post-test) | Date (pre-test) | Date (post-test) | Post-Test Hrs. | Tech. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SN: 16740739 | AF8902 25% ATJ - 75% JP8 | 1 | 3700 | 3450 | none | none | good | good | good | good | 3/24/14 | 7/7/14 | 210 | REG |
| | | | 2 | 3725 | 3600 | none | none | good | good | good | good | | | | |
| | | | 3 | 3700 | 3500 | none | none | good | good | good | good | | | | |
| | | | 4 | 3750 | 3550 | none | none | good | good | good | good | | | | |
| | | | Spec. : | 3050psig min | 3050psig min | no drop off in 10 sec. @ | no drop off in 10 sec. @ | chatter | chatter | fine mist | fine mist | | | | |

Comments : _____

_____
_____
_____
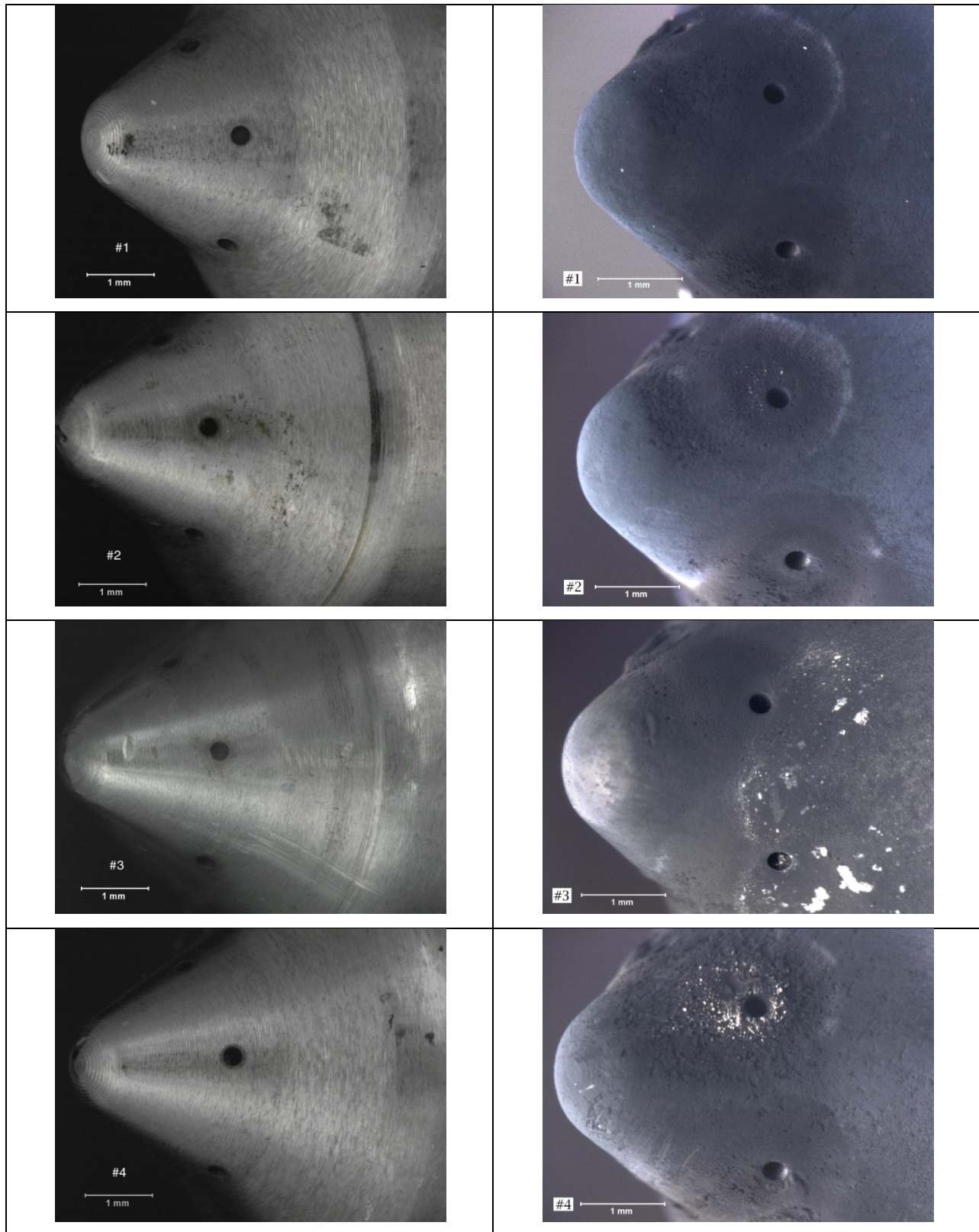
**Figure 30. Fuel Injector Tip Photos – Pre & Post Test**

### 4.7    USED OIL ANALYSIS

Table 10 shows the engine oil charge information for the 4045 engine. The engine was lubricated using an approved MIL-PRF-2104H SAE 15W-40 engine oil. Overall oil consumption over the course of the 210hr test was low at 0.016 lbs/hr.

**Table 10. 210hr Cycle Engine Oil Consumption**

| | | | Test Engine Lubricant Additions, Subtractions, and Consumption | | | | |
|---|---|---|---|---|---|---|---|

Lubricant: LO279606, MIL-PRF-2104H 15W40        Project No. 19555.01.101

**Initial Fill: (engine test)**

| | | Tech | Lubricant + Container Weight, lbs | - | Container Weight, lbs | = | Lubricant Weight, lbs |
|---|---|---|---|---|---|---|---|
| | | MX | unspecified | - | unspecified | = | 26.17 |
| | filter (wet/dry) | | 2.77 | - | 1.44 | = | 1.33 |
| | | | | | Total Initial Fill | = | 27.5 |

**Samples:**

| | Date | Tech | Sample + Container Weight, lbs | - | Container Weight, lbs | = | Sample Weight, lbs |
|---|---|---|---|---|---|---|---|
| 0 | 5/30/14 | MX | 0.31 | - | 0.06 | = | 0.25 |
| 21 | 5/31/14 | KE | 0.29 | - | 0.06 | = | 0.23 |
| 42 | 6/1/14 | KE | 0.30 | - | 0.06 | = | 0.24 |
| 63 | 6/2/14 | KE | 0.30 | - | 0.06 | = | 0.24 |
| 84 | 6/5/14 | RP | 0.31 | - | 0.06 | = | 0.25 |
| 105 | 6/6/14 | RP | 0.31 | - | 0.06 | = | 0.25 |
| 126 | 6/7/14 | DDA | 0.31 | - | 0.06 | = | 0.25 |
| 147 | 6/8/14 | DDA | 0.31 | - | 0.06 | = | 0.25 |
| 168 | 6/9/14 | RP | 0.31 | - | 0.06 | = | 0.25 |
| 189 | 6/10/14 | RP | 0.31 | - | 0.06 | = | 0.25 |
| 210 | 6/11/14 | MX | 0.31 | - | 0.06 | = | 0.25 |
| | | | | | Total Samples | = | 2.71 |

**Additions:**

| | Date | Tech | Addition + Container Weight, lbs | - | Container Weight, lbs | = | Addition Weight, lbs |
|---|---|---|---|---|---|---|---|
| 21 | 5/31/14 | KE | 0.64 | - | 0.24 | = | 0.40 |
| 42 | 6/1/14 | KE | 0.54 | - | 0.24 | = | 0.30 |
| 63 | 6/2/14 | KE | 0.53 | - | 0.24 | = | 0.29 |
| 84 | 6/5/14 | RP | 0.54 | - | 0.22 | = | 0.32 |
| 105 | 6/6/14 | RP | 0.54 | - | 0.22 | = | 0.32 |
| 126 | 6/7/14 | KE | 1.30 | - | 0.22 | = | 1.08 |
| 147 | 6/8/14 | KE | 1.25 | - | 0.22 | = | 1.03 |
| 168 | 6/9/14 | RP | 0.96 | - | 0.22 | = | 0.74 |
| 189 | 6/10/14 | RP | 1.03 | - | 0.22 | = | 0.81 |
| 210 | 6/24/14 | ACB | 0.00 | - | 0.00 | = | |
| | | | | | Total Additions | = | 5.29 |

**210-Hour Drain:***

| | | Tech | Lubricant + Container Weight, lbs | - | Container Weight, lbs | = | Lubricant Weight, lbs |
|---|---|---|---|---|---|---|---|
| | | MX | unspecified | - | unspecified | = | 26.3 |
| | filter (wet/dry) | | 1.87 | - | 1.44 | = | 0.43 |
| | | | | | Total 210-Hour Drain | = | 26.73 |

| | | |
|---|---|---|
| Total Initial Fill | 27.5 | [lbs] |
| Total Additions | 5.29 | [lbs] |
| Total Samples | 2.71 | [lbs] |
| Total 210-Hour Drain | 26.73 | [lbs] |
| Total 210-Hour OIL CONSUMPTION | 3.35 | [lbs] |
| Oil Consumption Rate (Oil Consumption/Test Hours) | 0.016 | [lbs/hr] |

Table 11 shows the tabulated used oil analysis results for the daily oil samples pulled from the engine. This was completed to ensure that the engine and lubricating oil remained in satisfactory condition, and to provide future information on oil sensitivity for the 4045 engine. Overall the engine oil degradation was low, which coincides with the relatively large engine oil sump volume for the engine size, and the normal oil operating temperature maintained over the test duration.

**Table 11. 210hr Cycle Used Oil Analysis**

| Property | ASTM Test | Test Hours | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 21 | 42 | 63 | 84 | 105 | 126 | 147 | 168 | 189 | 210 |
| Viscosity @ 100°C (cSt) | D445 | 15.5 | 14.6 | 14.3 | 14.2 | 14.2 | 14.2 | 14.2 | 14.2 | 14.4 | 14.3 | 14.4 |
| Total Base Number (mg KOH/g) | D4739 | 9.0 | 8.2 | 7.5 | 7.2 | 6.7 | 6.3 | 5.8 | 6.1 | 5.2 | 5.6 | 5.6 |
| Total Acid Number (mg KOH/g) | D664 | 2.1 | 2.1 | 2.2 | 2.3 | 2.5 | 2.5 | 2.5 | 2.6 | 2.6 | 2.5 | 2.5 |
| Oxidation (Abs./cm) | E168 FTNG | 0.0 | 0.7 | 1.1 | 1.5 | 1.7 | 1.9 | 2.1 | 2.2 | 2.6 | 2.7 | 2.8 |
| Nitration (Abs./cm) | E168 FTNG | 0.0 | 0.0 | 0.0 | 0.3 | 0.4 | 0.5 | 0.6 | 0.6 | 0.7 | 0.8 | 0.8 |
| Soot | Soot | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.5 | 0.3 | 0.3 | 0.4 | 0.4 |
| Wear Metals (ppm) | D5185 | | | | | | | | | | | |
| Al | | 1 | 1 | <1 | <1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Sb | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Ba | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| B | | 8 | 10 | 9 | 9 | 9 | 9 | 8 | 9 | 7 | 8 | 7 |
| Ca | | 2343 | 2342 | 2384 | 2360 | 2405 | 2393 | 2386 | 2390 | 2443 | 2451 | 2415 |
| Cr | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Cu | | <1 | <1 | <1 | <1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| Fe | | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 15 | 17 | 20 | 20 |
| Pb | | <1 | <1 | <1 | <1 | <1 | 2 | 2 | 2 | 2 | 2 | 3 |
| Mg | | 305 | 316 | 309 | 308 | 323 | 317 | 308 | 306 | 319 | 323 | 303 |
| Mn | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Mo | | 7 | 9 | 9 | 10 | 10 | 10 | 10 | 9 | 9 | 9 | 9 |
| Ni | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| P | | 1267 | 1248 | 1250 | 1242 | 1223 | 1219 | 1209 | 1206 | 1216 | 1203 | 1188 |
| Si | | 5 | 3 | 4 | 4 | 5 | 6 | 7 | 6 | 7 | 7 | 7 |
| Ag | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Na | | <5 | <5 | <5 | <5 | <5 | <5 | 5 | 7 | <5 | <5 | 5 |
| Sn | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Zn | | 1383 | 1391 | 1408 | 1405 | 1413 | 1406 | 1398 | 1398 | 1424 | 1419 | 1400 |
| K | | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| Sr | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| V | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Ti | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Cd | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |

Figure 31 through Figure 35 graphically present selected used oil analysis parameters from the table above for further review.
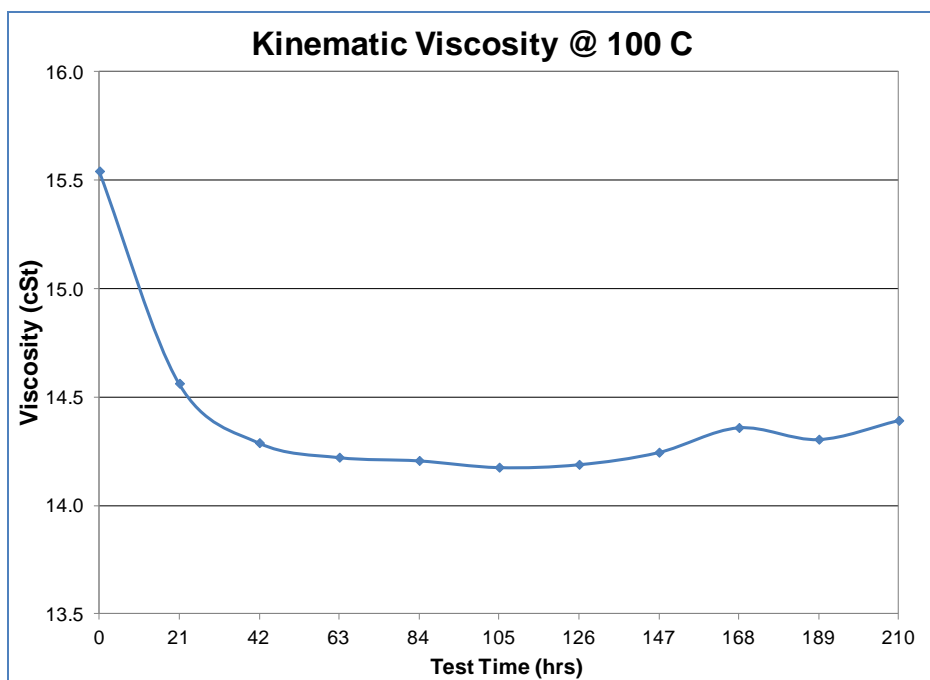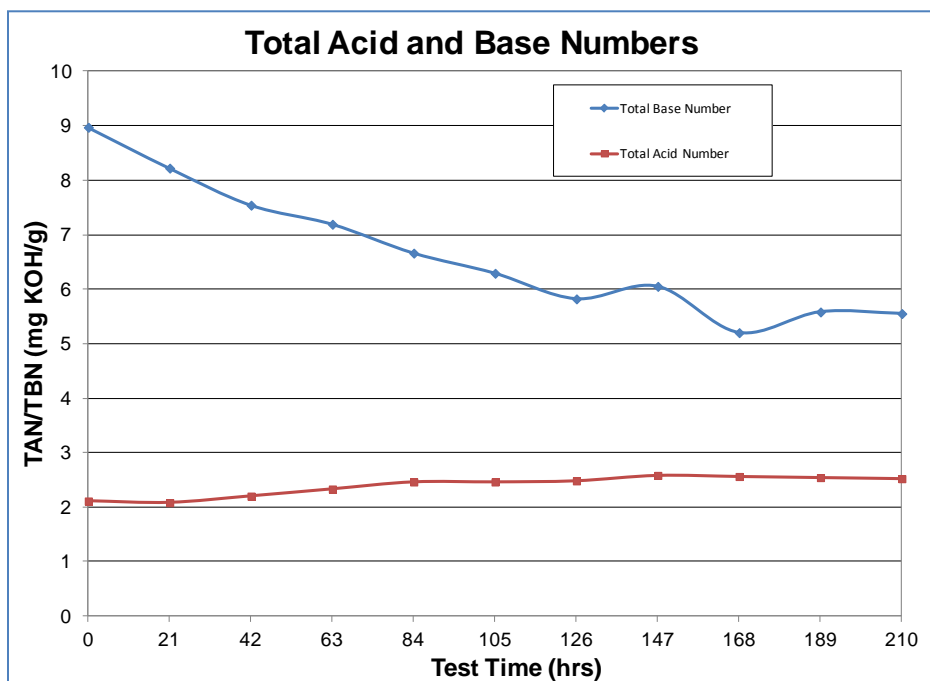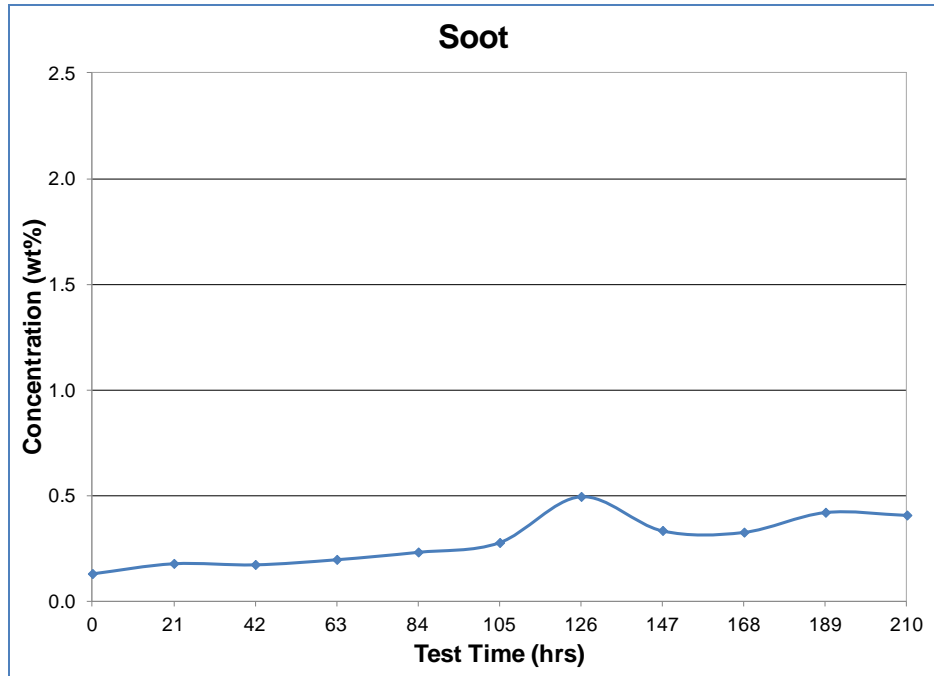
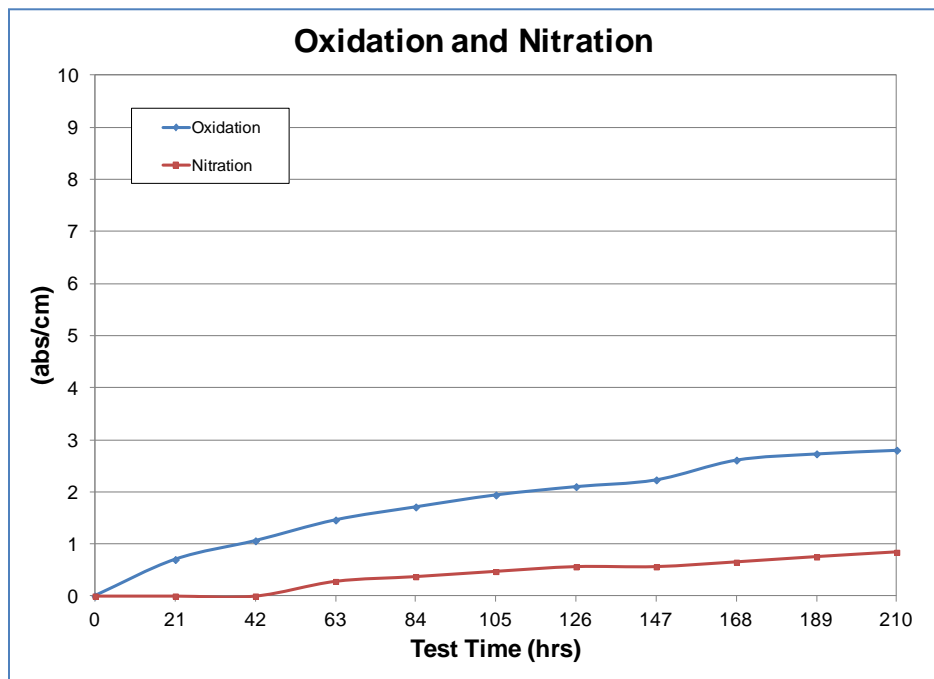**Figure 31. 100°C Kinematic Viscosity Response**



**Figure 32. TAN/TBN Response**

**Soot**



**Figure 33. Soot Accumulation**

**Oxidation and Nitration**



**Figure 34. Oxidation and Nitration Response**
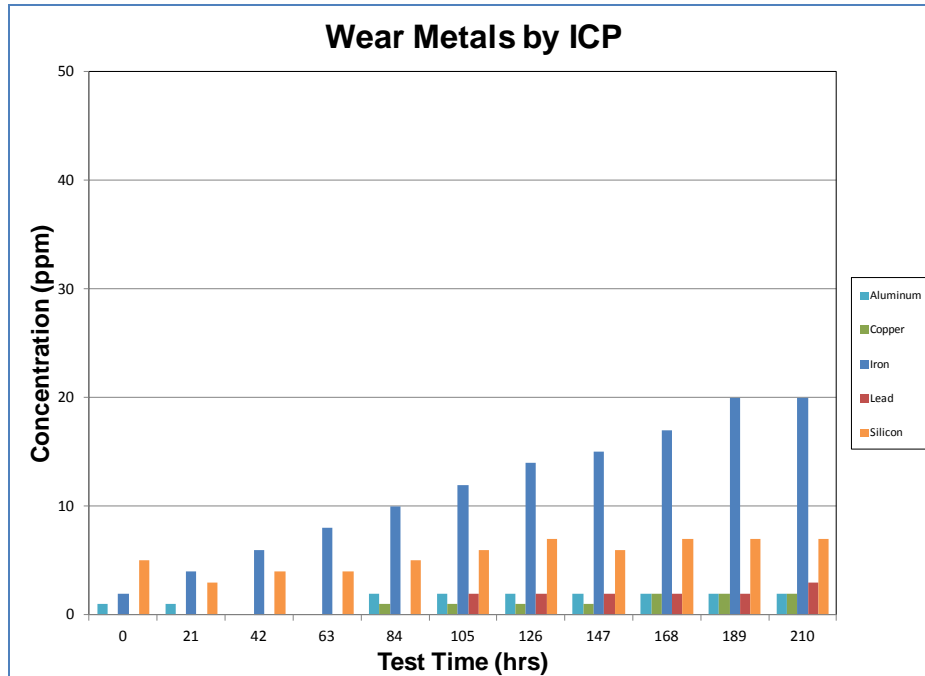
**Wear Metals by ICP**



**Figure 35. Used Oil Elemental Analysis**

## 5.0    CONCLUSIONS

The John Deere 4045HF280 engine successfully completed the 25% ATJ fuel blend evaluation following the 210hr Tactical Wheeled Vehicle Cycle protocol. The unusually low cetane value for the ATJ blending stock limited the total volumetric quantity of ATJ to 25% in the overall blend, but apart from the cetane value itself, the resulting ATJ blend retained similar chemical and physical properties as the baseline JP8 evaluated. Both fuels successfully completed the pre and post test full and partial load power curves with similar results, and with the exception of the unusual operation at high speed and low loads at DOC, both fuels performed as expected in all evaluations. The high temperature high speed low load operation deviation in the 4045 engine is unusual, and currently remains unexplained, but since both the ATJ blend and JP8 baseline fuels experienced this issue, it provides no grounds to consider the ATJ blend incompatible in place of the JP8. Further in-depth cylinder pressure analysis would be required to determine the cause of the high temperate operating shift for both fuels, but apart from higher fuel consumption and exhaust emissions changes, the engine still performed as desired producing the specified power level at the high speed condition.

The engine operated on the 25% ATJ blend over the full 210hr duration and experienced no operational issues. Performance degradation experienced across the test duration was on par with typical results for military fuels in rotary style injection pumps. The primary changes noted in the injection hardware were an overall reduction of injected fuel flow, especially evident at the high speed conditions. This type of wear can be typical in these types of systems, but the engine continued to perform and function as it should. Overall the ATJ blend was compatible with the 4045HF280 engine, and results from testing support the use of the 25% AJT blend in similar equipment.

# 6.0    REFERENCES

1.    "The Basics." *Renewable Jet Fuels*. Web. <http://renewablejetfuels.org/what-we-do/the-basics#terminology>.

2.    Development of Military Fuel/Lubricant/Engine Compatibility Test, CRC Report 406, January 1967

**APPENDIX A.**

**John Deere 4045HF280 Emissions Measurements**

**Table A-1.  Pre & Post Test Powercurve Emissions (Full Tabulated Results)**

| Range | 0-3000 | 0-16 | 0-5000 | 0-25 | 0-2000 | | | Range | 0-3000 | 0-16 | 0-5000 | 0-25 | 0-2000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CO-L | CO2 | NO/NOx | O2 | THC | BOSCH Smk No | | | CO-L | CO2 | NO/NOx | O2 | THC | BOSCH Smk No |
| | ppm | % | ppm | % | ppm C | 2 pumps | | | ppm | % | ppm | % | ppm C | 2 pumps |
| 1200_25 | 156.92 | 3.63 | 214.06 | 16.10 | 184.20 | 0.0 | | 1200_25 | 202.53 | 3.59 | 224.30 | 16.85 | 186.54 | 0.0 |
| 1600_25 | 155.35 | 4.10 | 180.49 | 15.46 | 183.46 | 0.6 | | 1600_25 | 191.42 | 4.00 | 202.44 | 16.25 | 199.50 | 0.0 |
| 1900_25 | 129.15 | 4.39 | 196.57 | 15.03 | 159.65 | 0.8 | | 1900_25 | 163.84 | 4.33 | 207.03 | 15.76 | 185.04 | 0.2 |
| 2100_25 | 158.29 | 4.42 | 192.09 | 14.96 | 153.06 | 2.1 | | 2100_25 | 161.09 | 4.32 | 203.48 | 15.72 | 167.09 | 1.5 |
| 2400_25 | 204.57 | 4.35 | 163.00 | 15.02 | 166.06 | 2.2 | | 2400_25 | 212.75 | 4.27 | 171.04 | 15.74 | 177.42 | 2.0 |
| 1200_50 | 91.04 | 5.78 | 335.99 | 13.01 | 152.12 | 0.4 | | 1200_50 | 111.55 | 5.65 | 375.72 | 13.78 | 177.98 | 0.3 |
| 1600_50 | 129.51 | 6.04 | 292.48 | 12.59 | 149.20 | 0.3 | | 1600_50 | 182.30 | 5.93 | 335.78 | 13.32 | 159.09 | 0.0 |
| 1900_50 | 146.94 | 6.06 | 259.40 | 12.54 | 144.72 | 0.4 | | 1900_50 | 242.26 | 5.91 | 275.84 | 13.33 | 180.60 | 0.0 |
| 2100_50 | 119.22 | 5.84 | 230.52 | 12.84 | 150.28 | 0.9 | | 2100_50 | 154.67 | 5.75 | 242.66 | 13.53 | 159.55 | 0.2 |
| 2400_50 | 145.18 | 5.53 | 182.21 | 13.27 | 164.29 | 1.0 | | 2400_50 | 169.35 | 5.39 | 192.59 | 14.00 | 170.54 | 0.8 |
| 1200_75 | 74.86 | 7.65 | 511.94 | 10.23 | 175.41 | 1.5 | | 1200_75 | 75.57 | 7.56 | 489.49 | 10.92 | 198.55 | 1.4 |
| 1600_75 | 59.03 | 7.36 | 382.44 | 10.63 | 127.42 | 0.9 | | 1600_75 | 62.48 | 7.23 | 371.48 | 11.38 | 141.99 | 0.8 |
| 1900_75 | 86.28 | 7.08 | 301.81 | 11.01 | 118.24 | 0.8 | | 1900_75 | 92.58 | 6.90 | 296.48 | 11.84 | 121.05 | 0.9 |
| 2100_75 | 108.34 | 6.71 | 268.42 | 11.53 | 85.33 | 1.7 | | 2100_75 | 117.03 | 6.59 | 263.15 | 12.27 | 83.19 | 1.4 |
| 2400_75 | 114.20 | 6.25 | 239.88 | 12.18 | 92.92 | 1.8 | | 2400_75 | 115.00 | 6.10 | 234.45 | 12.95 | 91.31 | 1.4 |
| 1200_100 | 76.90 | 7.73 | 525.27 | 10.06 | 174.98 | 1.5 | | 1200_100 | 75.71 | 7.59 | 509.68 | 10.84 | 197.55 | 1.4 |
| 1600_100 | 58.54 | 7.54 | 425.01 | 10.31 | 127.41 | 1.1 | | 1600_100 | 58.50 | 7.46 | 408.16 | 11.00 | 138.10 | 0.8 |
| 1900_100 | 80.05 | 7.41 | 365.47 | 10.47 | 110.26 | 1.2 | | 1900_100 | 82.52 | 7.36 | 356.83 | 11.14 | 112.03 | 1.4 |
| 2100_100 | 113.93 | 7.00 | 304.33 | 11.05 | 103.80 | 1.7 | | 2100_100 | 120.70 | 6.97 | 295.64 | 11.67 | 107.92 | 1.4 |
| 2400_100 | 99.45 | 6.43 | 257.81 | 11.86 | 54.22 | 2.1 | | 2400_100 | 107.94 | 6.40 | 250.03 | 12.45 | 61.93 | 1.7 |

*Left block: PRE TEST, AMBIENT, JP8 — Right block: PRE TEST, AMBIENT, 25% ATJ 75% JP8*

| Range | CO-L | | NO/NOx | | THC | BOSCH Smk No | | | CO-L | | NO/NOx | | THC | BOSCH Smk No |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ppm | % | ppm | % | ppm C | 2 pumps | | | ppm | % | ppm | % | ppm C | 2 pumps |
| 1200_25 | 399.11 | 3.89 | 209.86 | 15.66 | 298.04 | 0.0 | | 1200_25 | 855.44 | 3.87 | 211.42 | 16.14 | 580.35 | 0.0 |
| 1600_25 | 1309.30 | 4.50 | 143.81 | 14.70 | 959.28 | 0.0 | | 1600_25 | 2121.50 | 4.44 | 121.62 | 15.16 | >2000 | 0.0 |
| 1900_25 | 1983.70 | 4.79 | 103.67 | 14.15 | >2000 | 0.0 | | 1900_25 | 2292.00 | 4.84 | 104.36 | 14.54 | >2000 | 0.0 |
| 2100_25 | 502.18 | 4.74 | 168.43 | 14.55 | 430.33 | 0.0 | | 2100_25 | 2285.00 | 4.84 | 98.75 | 14.51 | >2000 | 0.0 |
| 2400_25 | 234.95 | 4.59 | 150.32 | 14.58 | 281.02 | 0.4 | | 2400_25 | 349.19 | 4.50 | 172.04 | 15.21 | 483.15 | 0.0 |
| 1200_50 | 88.68 | 6.01 | 327.99 | 12.79 | 214.71 | 0.6 | | 1200_50 | 91.82 | 5.91 | 394.30 | 13.21 | 314.59 | 0.2 |
| 1600_50 | 110.73 | 6.28 | 289.17 | 12.39 | 188.46 | 0.4 | | 1600_50 | 166.84 | 6.14 | 340.71 | 12.86 | 272.07 | 0.2 |
| 1900_50 | 180.33 | 6.33 | 258.51 | 12.29 | 179.71 | 0.4 | | 1900_50 | 314.55 | 6.20 | 299.46 | 12.75 | 280.42 | 0.2 |
| 2100_50 | 239.44 | 6.16 | 230.15 | 12.48 | 212.65 | 0.3 | | 2100_50 | 446.61 | 6.05 | 260.15 | 12.91 | 344.41 | 0.2 |
| 2400_50 | 254.42 | 5.76 | 181.07 | 13.03 | 227.29 | 0.5 | | 2400_50 | 568.11 | 5.64 | 194.94 | 13.44 | 425.69 | 0.2 |
| 1200_75 | 70.19 | 7.16 | 411.69 | 11.05 | 216.28 | 1.2 | | 1200_75 | 66.54 | 7.04 | 440.10 | 11.50 | 268.82 | 1.1 |
| 1600_75 | 86.72 | 6.65 | 303.27 | 11.75 | 184.98 | 0.9 | | 1600_75 | 105.39 | 6.46 | 339.20 | 12.31 | 215.15 | 0.5 |
| 1900_75 | 112.52 | 7.00 | 276.95 | 11.24 | 173.05 | 1.2 | | 1900_75 | 115.96 | 6.85 | 300.55 | 11.74 | 191.30 | 1.2 |
| 2100_75 | 143.57 | 6.80 | 250.49 | 11.52 | 174.78 | 1.5 | | 2100_75 | 150.04 | 6.62 | 270.09 | 12.05 | 185.78 | 1.4 |
| 2400_75 | 151.93 | 6.23 | 196.37 | 12.30 | 166.50 | 1.2 | | 2400_75 | 198.80 | 6.03 | 213.70 | 12.87 | 199.40 | 0.7 |
| 1200_100 | | | | | | | | 1200_100 | | | | | | |
| 1600_100 | | | | | | | | 1600_100 | | | | | | |
| 1900_100 | | | | | | | | 1900_100 | | | | | | |
| 2100_100 | | | | | | | | 2100_100 | | | | | | |
| 2400_100 | | | | | | | | 2400_100 | | | | | | |

*Left block: PRE TEST, DESERT, JP8 — Right block: PRE TEST, DESERT, 25% ATJ 75% JP8*

## Table A-2.  Pre & Post Test Powercurve Emissions (Full Tabulated Results) CONT.

**POST TEST, AMBIENT, JP8**

| Range | 0-3000 | 0-16 | 0-5000 | 0-25 | 0-2000 | BOSCH Smk No |
|---|---|---|---|---|---|---|
| | CO-L | | NO/NOx | | THC | |
| | ppm | % | ppm | % | ppm C | 2 pumps |
| 1200_25 | 168.28 | 3.73 | 225.24 | 16.47 | 170.19 | 0.1 |
| 1600_25 | 168.58 | 4.28 | 180.86 | 15.72 | 174.44 | 0.4 |
| 1900_25 | 140.91 | 4.62 | 200.94 | 15.22 | 156.42 | 0.8 |
| 2100_25 | 156.30 | 4.60 | 191.16 | 15.23 | 147.89 | 1.7 |
| 2400_25 | 200.05 | 4.56 | 162.12 | 15.23 | 158.27 | 2.1 |
| 1200_50 | 88.08 | 5.87 | 350.96 | 13.35 | 132.22 | 0.4 |
| 1600_50 | 121.57 | 6.22 | 295.53 | 12.81 | 123.69 | 0.5 |
| 1900_50 | 169.89 | 6.29 | 263.67 | 12.67 | 145.22 | 0.4 |
| 2100_50 | 128.19 | 6.11 | 238.65 | 12.91 | 140.69 | 0.5 |
| 2400_50 | 152.50 | 5.67 | 186.59 | 13.52 | 151.51 | 1.2 |
| 1200_75 | 113.07 | 7.78 | 510.97 | 10.50 | 158.45 | 2.6 |
| 1600_75 | 64.94 | 7.54 | 396.79 | 10.83 | 129.53 | 1.1 |
| 1900_75 | 87.80 | 7.31 | 312.43 | 11.15 | 120.02 | 1.3 |
| 2100_75 | 107.21 | 7.00 | 273.76 | 11.59 | 100.61 | 1.4 |
| 2400_75 | 122.61 | 6.40 | 243.35 | 12.43 | 106.31 | 1.7 |
| 1200_100 | 118.56 | 7.78 | 513.65 | 10.46 | 167.52 | 1.9 |
| 1600_100 | 66.13 | 7.67 | 424.35 | 10.61 | 132.25 | 1.5 |
| 1900_100 | 87.13 | 7.73 | 379.09 | 10.52 | 114.35 | 1.4 |
| 2100_100 | 110.95 | 7.32 | 317.38 | 11.07 | 106.98 | 1.7 |
| 2400_100 | 111.24 | 6.56 | 257.21 | 12.13 | 55.68 | 1.7 |

**POST TEST, AMBIENT, 25% ATJ 75% JP8**

| Range | 0-3000 | 0-16 | 0-5000 | 0-25 | 0-2000 | BOSCH Smk No |
|---|---|---|---|---|---|---|
| | CO-L | | NO/NOx | | THC | |
| | ppm | % | ppm | % | ppm C | 2 pumps |
| 1200_25 | 239.23 | 3.70 | 248.84 | 15.82 | 186.10 | 0.1 |
| 1600_25 | 208.39 | 4.22 | 216.81 | 15.04 | 175.33 | 0.0 |
| 1900_25 | 185.81 | 4.58 | 224.28 | 14.50 | 168.16 | 0.3 |
| 2100_25 | 174.28 | 4.60 | 208.89 | 14.42 | 153.61 | 1.6 |
| 2400_25 | 227.53 | 4.52 | 171.22 | 14.48 | 166.91 | 1.5 |
| 1200_50 | 110.75 | 5.82 | 380.71 | 12.60 | 133.83 | 0.3 |
| 1600_50 | 189.28 | 6.18 | 327.88 | 12.04 | 140.22 | 0.3 |
| 1900_50 | 272.29 | 6.26 | 286.30 | 11.88 | 177.26 | 0.4 |
| 2100_50 | 170.04 | 6.07 | 254.43 | 12.13 | 144.84 | 0.4 |
| 2400_50 | 189.10 | 5.65 | 195.87 | 12.72 | 157.14 | 0.6 |
| 1200_75 | 123.18 | 7.73 | 498.89 | 9.75 | 178.81 | 2.4 |
| 1600_75 | 67.88 | 7.58 | 397.89 | 9.96 | 132.04 | 1.3 |
| 1900_75 | 97.37 | 7.26 | 312.69 | 10.40 | 115.88 | 1.3 |
| 2100_75 | 122.79 | 6.94 | 274.50 | 10.85 | 110.48 | 1.4 |
| 2400_75 | 126.61 | 6.36 | 240.76 | 11.66 | 105.58 | 1.5 |
| 1200_100 | 129.88 | 7.73 | 499.52 | 9.70 | 172.78 | 2.2 |
| 1600_100 | 68.31 | 7.58 | 408.54 | 9.91 | 133.23 | 1.2 |
| 1900_100 | 92.36 | 7.60 | 355.80 | 9.87 | 106.02 | 1.3 |
| 2100_100 | 116.87 | 7.22 | 308.91 | 10.39 | 104.01 | 1.4 |
| 2400_100 | 115.41 | 6.56 | 251.30 | 11.30 | 49.68 | 1.7 |

**POST TEST, DESERT, JP8**

| Range | CO-L | | NO/NOx | | THC | BOSCH Smk No |
|---|---|---|---|---|---|---|
| | ppm | % | ppm | % | ppm C | 2 pumps |
| 1200_25 | 324.54 | 3.95 | 229.41 | 15.64 | 244.35 | 0.0 |
| 1600_25 | 744.21 | 4.54 | 196.21 | 14.74 | 465.21 | 0.0 |
| 1900_25 | 1761.70 | 5.07 | 122.10 | 13.87 | 1706.10 | 0.0 |
| 2100_25 | 933.15 | 5.04 | 147.84 | 14.00 | 734.03 | 0.0 |
| 2400_25 | 228.04 | 4.82 | 157.36 | 14.37 | 234.20 | 0.4 |
| 1200_50 | 89.41 | 6.14 | 326.45 | 12.44 | 178.96 | 0.8 |
| 1600_50 | 107.59 | 6.47 | 286.90 | 11.92 | 161.14 | 0.6 |
| 1900_50 | 172.13 | 6.55 | 274.06 | 11.74 | 157.28 | 0.8 |
| 2100_50 | 232.25 | 6.42 | 244.91 | 11.90 | 201.31 | 0.4 |
| 2400_50 | 229.02 | 5.99 | 187.65 | 12.48 | 195.13 | 0.4 |
| 1200_75 | 79.45 | 7.24 | 394.59 | 10.68 | 176.05 | 1.5 |
| 1600_75 | 93.21 | 6.74 | 286.18 | 11.38 | 154.01 | 0.9 |
| 1900_75 | 122.33 | 7.20 | 273.02 | 10.71 | 152.46 | 1.5 |
| 2100_75 | 148.99 | 7.09 | 257.62 | 10.87 | 152.66 | 1.5 |
| 2400_75 | 166.81 | 6.33 | 192.62 | 11.95 | 153.51 | 1.0 |
| 1200_100 | | | | | | |
| 1600_100 | | | | | | |
| 1900_100 | | | | | | |
| 2100_100 | | | | | | |
| 2400_100 | | | | | | |

**POST TEST, DESERT, 25% ATJ 75% JP8**

| Range | CO-L | | NO/NOx | | THC | BOSCH Smk No |
|---|---|---|---|---|---|---|
| | ppm | % | ppm | % | ppm C | 2 pumps |
| 1200_25 | 794.36 | 4.02 | 201.13 | 15.41 | 477.36 | 0.0 |
| 1600_25 | 2007.80 | 4.79 | 111.07 | 14.14 | >2000 | 0.0 |
| 1900_25 | 2195.20 | 5.20 | 101.84 | 13.51 | >2000 | 0.0 |
| 2100_25 | 2208.10 | 5.24 | 98.03 | 13.46 | >2000 | 0.0 |
| 2400_25 | 575.21 | 4.83 | 145.49 | 14.26 | 585.22 | 0.0 |
| 1200_50 | 104.07 | 6.14 | 355.11 | 12.38 | 238.87 | 0.6 |
| 1600_50 | 152.74 | 6.42 | 318.63 | 11.90 | 215.06 | 0.3 |
| 1900_50 | 305.72 | 6.53 | 276.95 | 11.68 | 236.76 | 0.8 |
| 2100_50 | 440.33 | 6.40 | 242.66 | 11.82 | 317.76 | 0.2 |
| 2400_50 | 439.85 | 5.96 | 187.73 | 12.43 | 305.51 | 0.3 |
| 1200_75 | 79.24 | 7.21 | 394.75 | 10.66 | 210.68 | 1.4 |
| 1600_75 | 116.27 | 6.62 | 319.24 | 11.49 | 169.20 | 0.8 |
| 1900_75 | 145.37 | 7.08 | 281.28 | 10.83 | 176.90 | 1.1 |
| 2100_75 | 163.50 | 7.03 | 261.52 | 10.89 | 169.55 | 1.3 |
| 2400_75 | 218.56 | 6.33 | 204.71 | 11.88 | 176.92 | 0.8 |
| 1200_100 | | | | | | |
| 1600_100 | | | | | | |
| 1900_100 | | | | | | |
| 2100_100 | | | | | | |
| 2400_100 | | | | | | |

**APPENDIX B.**

**Fuel Injector Photos**

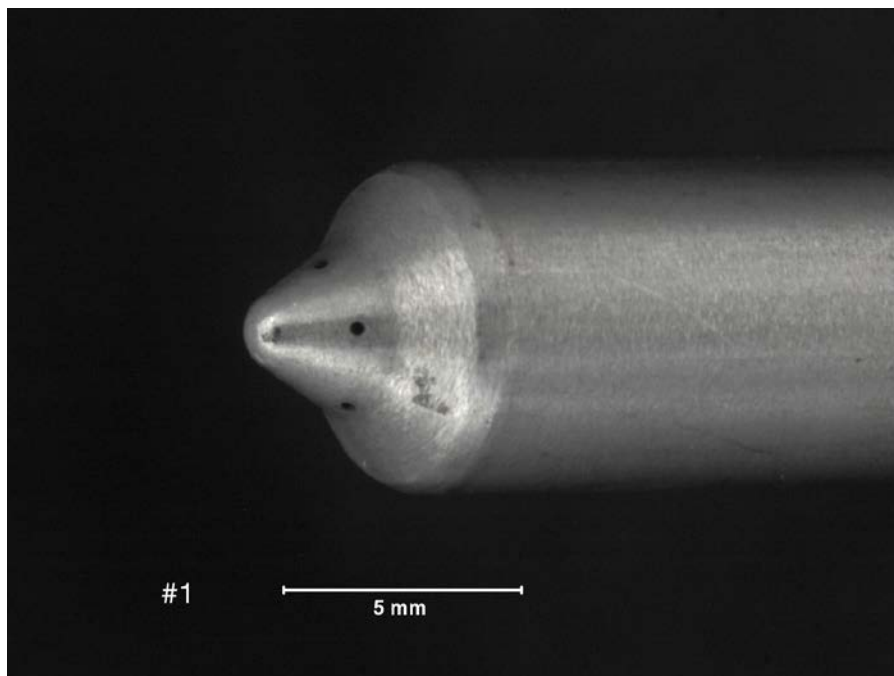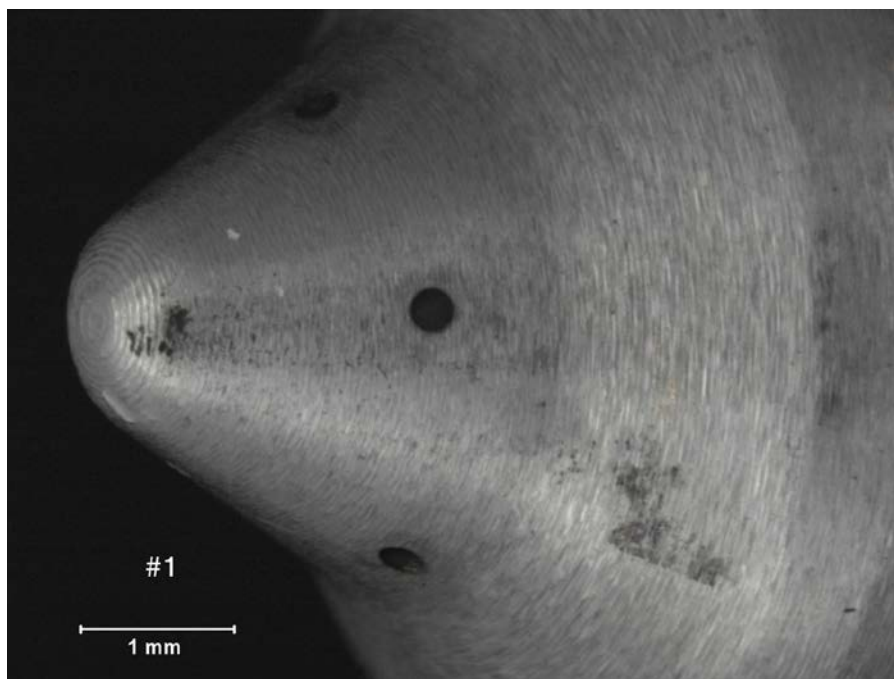**Figure B-1. Pre-Test Injector Tip, Injector 1**
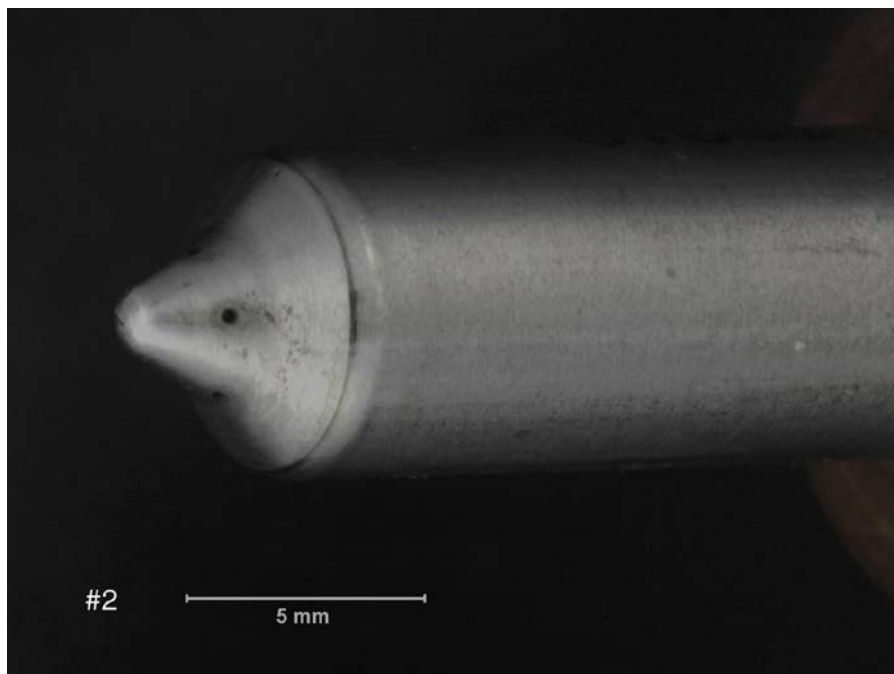


**Figure B-2. Pre-Test Injector Tip, Injector 1 (Close)**
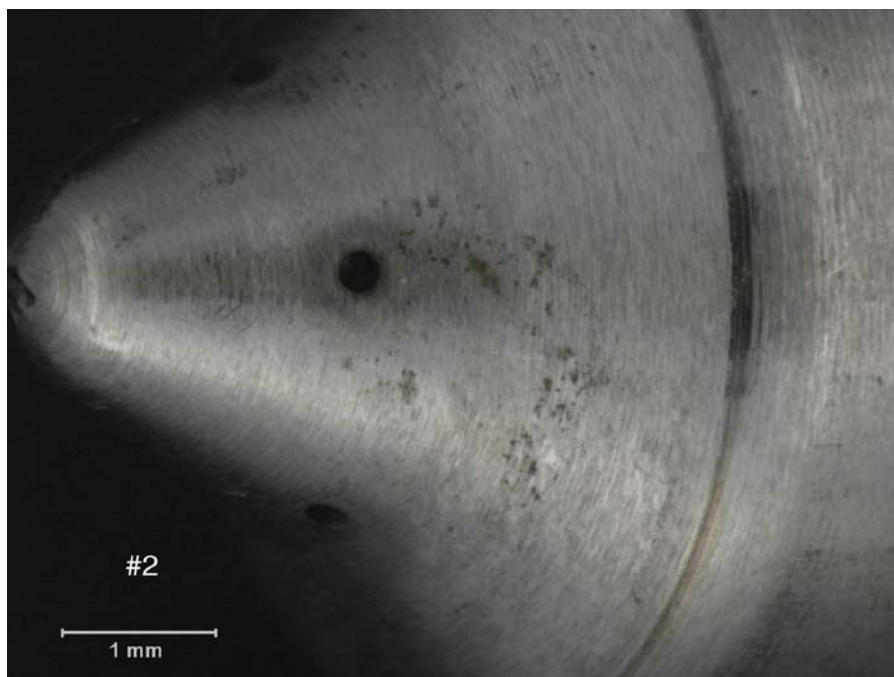
**Figure B-3. Pre-Test Injector Tip, Injector 2**
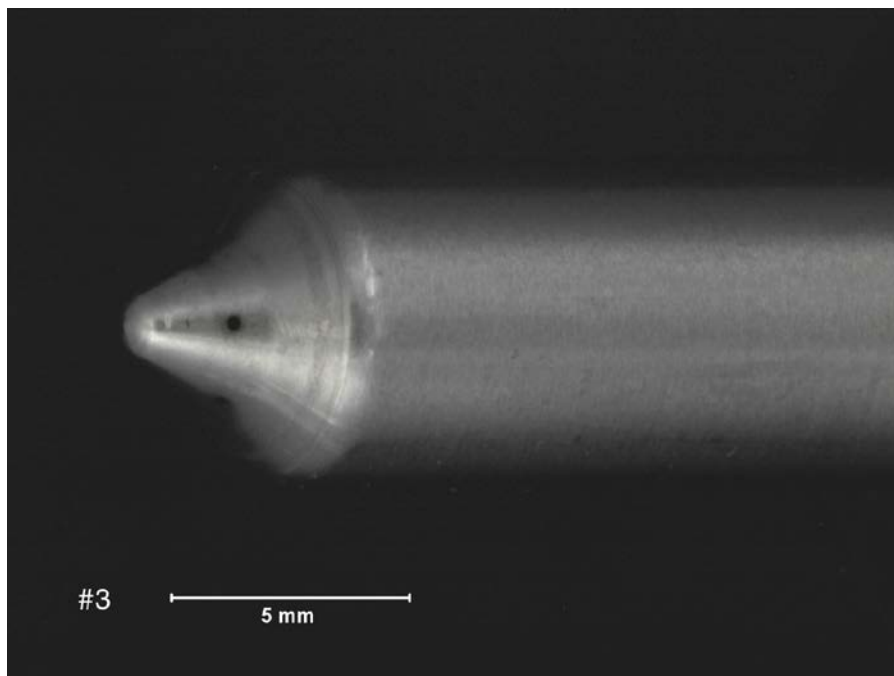


**Figure B-4. Pre-Test Injector Tip, Injector 2 (Close)**
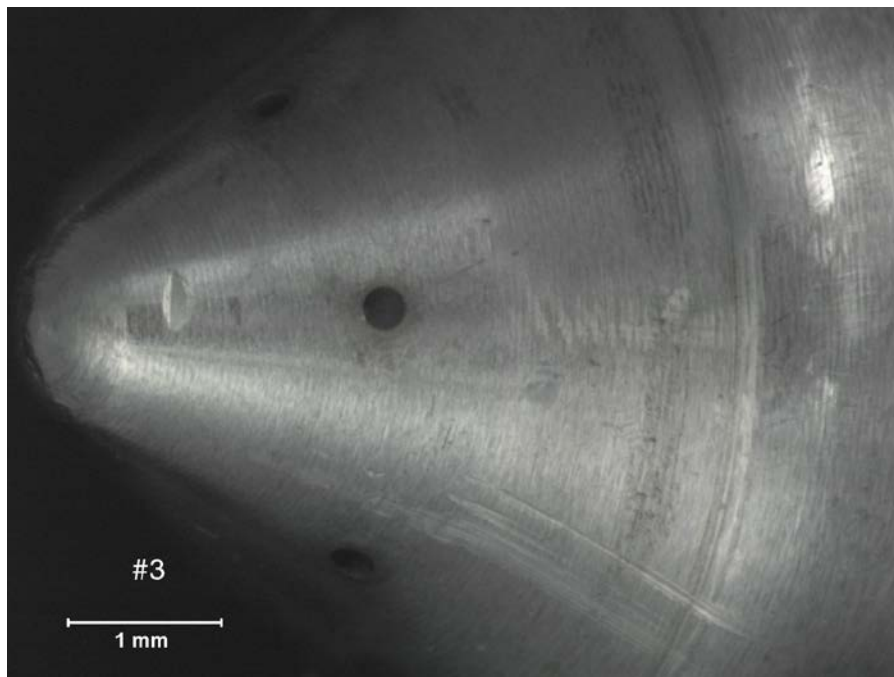
**Figure B-5.  Pre-Test Injector Tip, Injector 3**



**Figure B-6.  Pre-Test Injector Tip, Injector 3 (Close)**
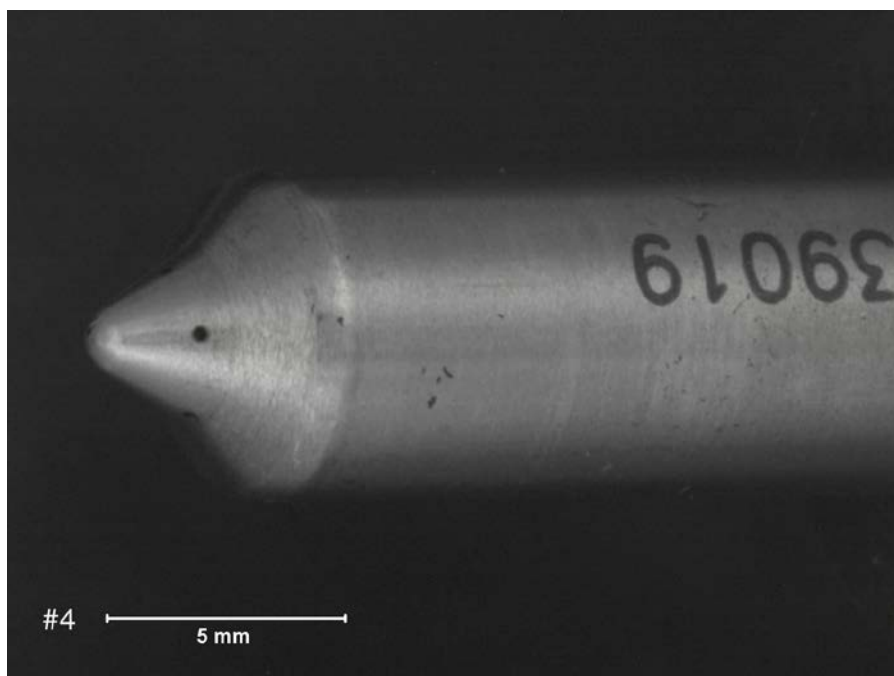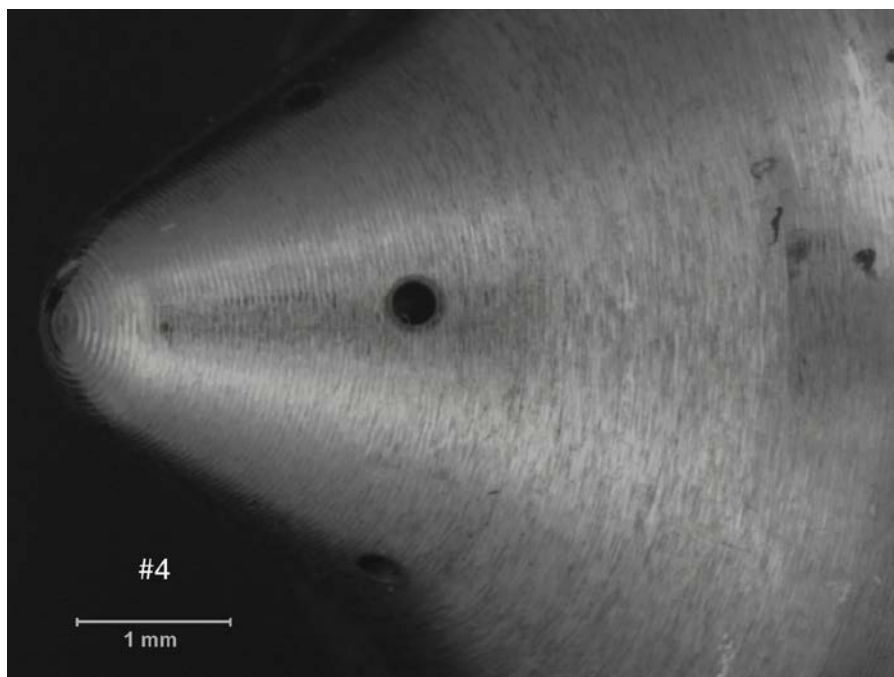
**Figure B-7.  Pre-Test Injector Tip, Injector 4**



**Figure B-8.  Pre-Test Injector Tip, Injector 4 (Close)**
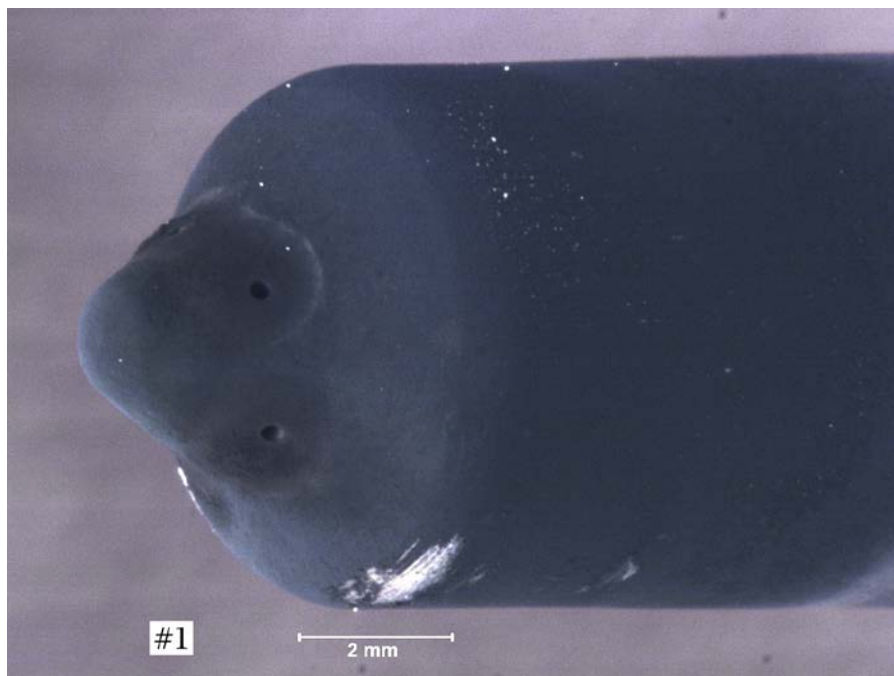
**Figure B-9.  Post-Test Injector Tip, Injector 1**
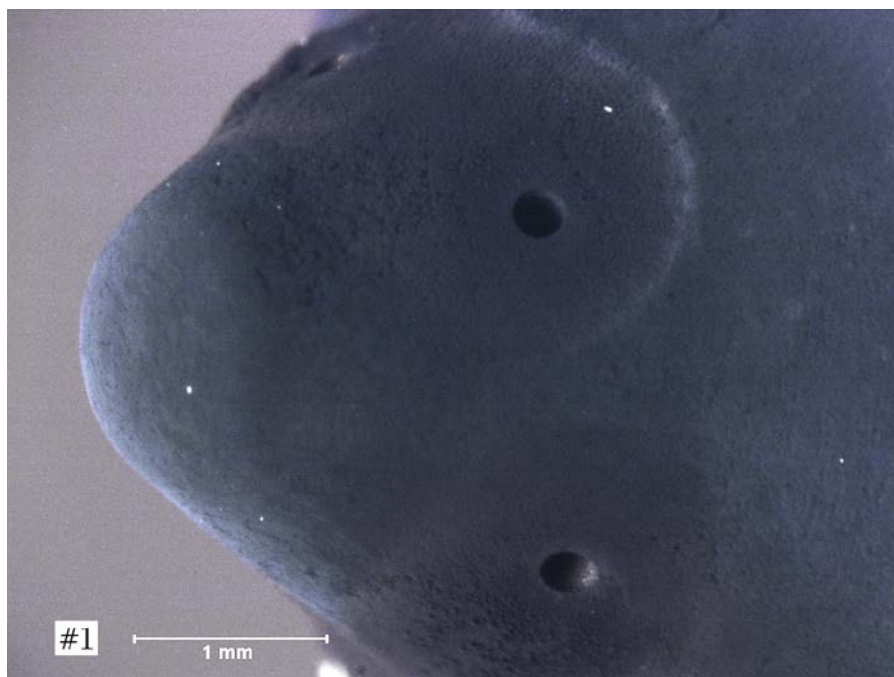


**Figure B-10.  Post-Test Injector Tip, Injector 1 (Close)**
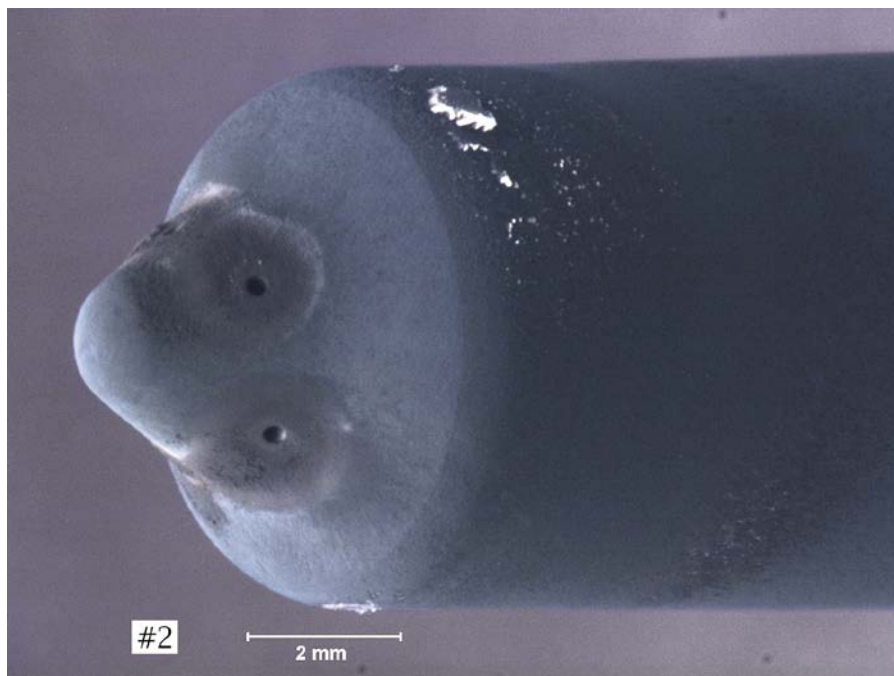
**Figure B-11.  Post-Test Injector Tip, Injector 2**
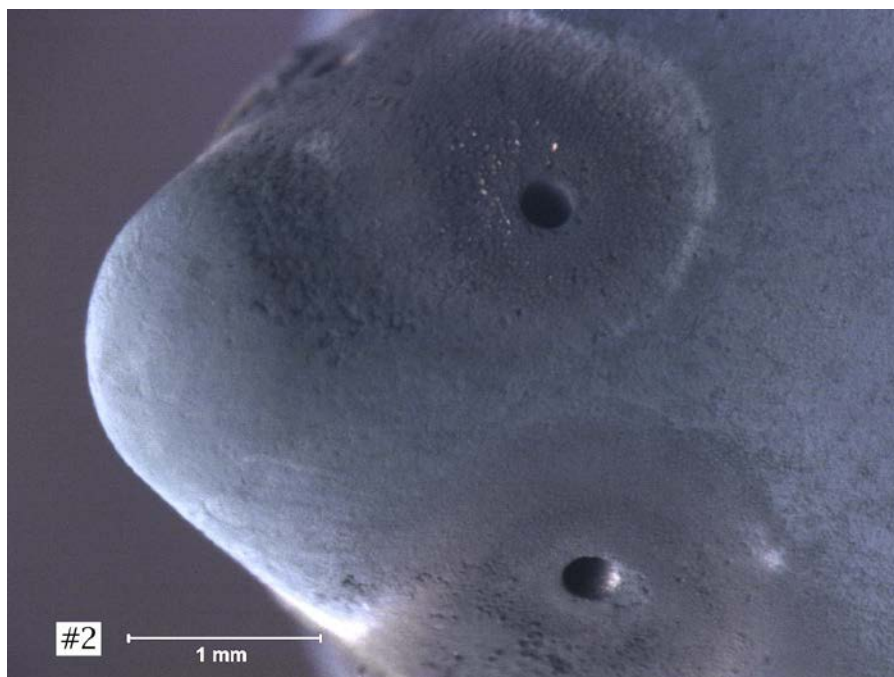


**Figure B-12.  Post-Test Injector Tip, Injector 2 (Close)**
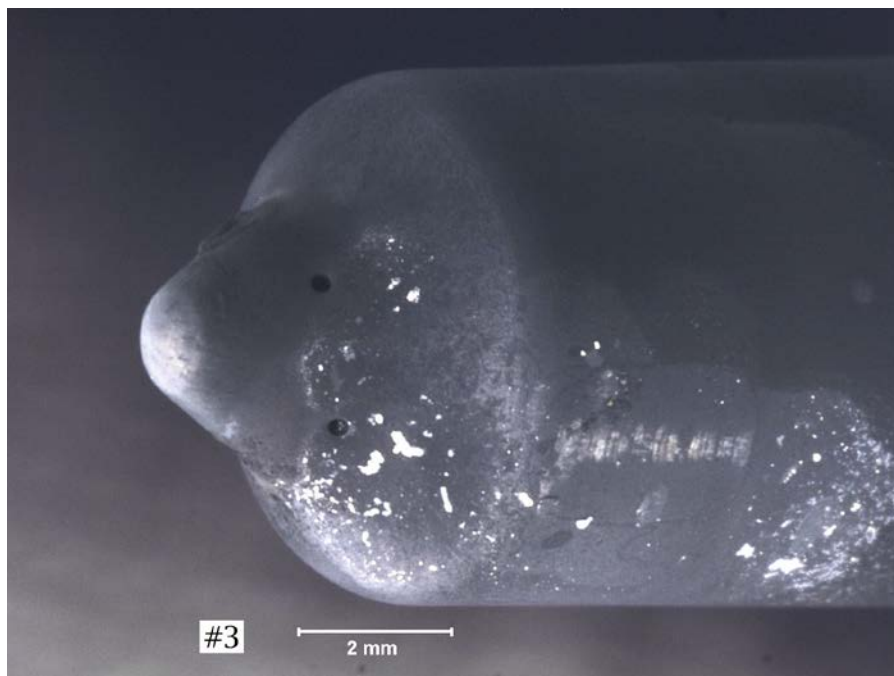
**Figure B-13.  Post-Test Injector Tip, Injector 3**
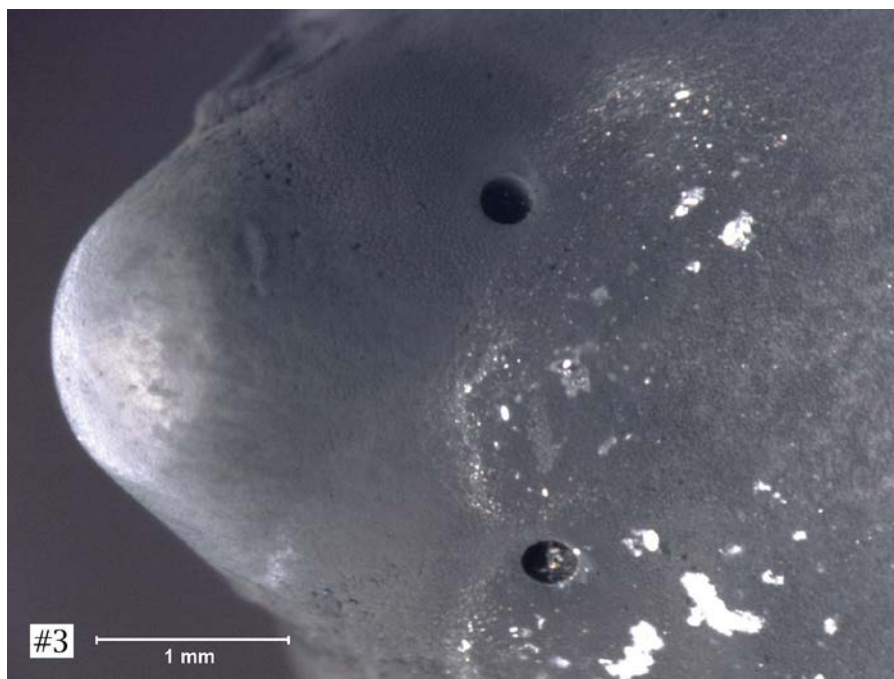


**Figure B-14.  Post-Test Injector Tip, Injector 3 (Close)**

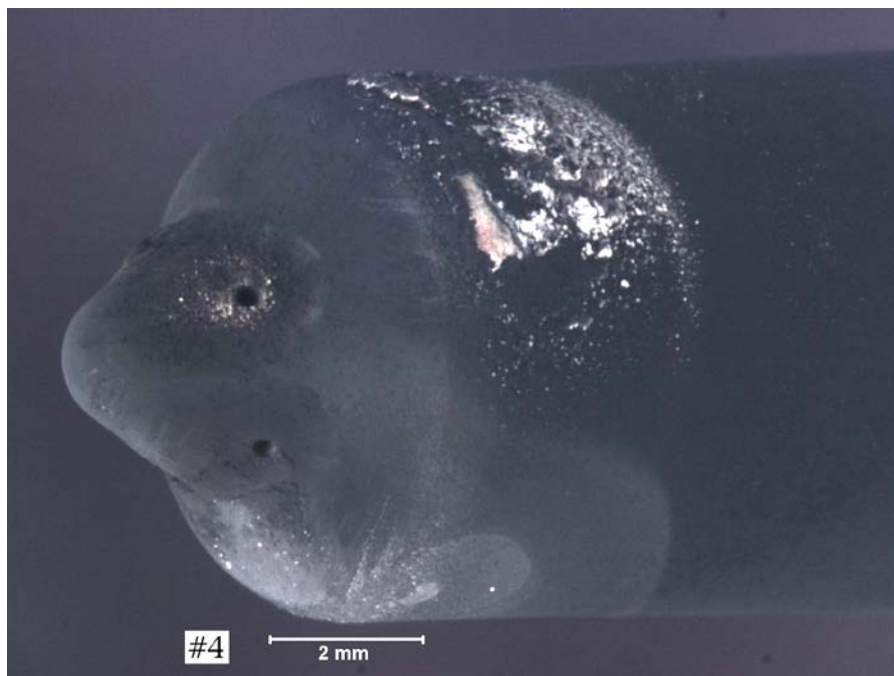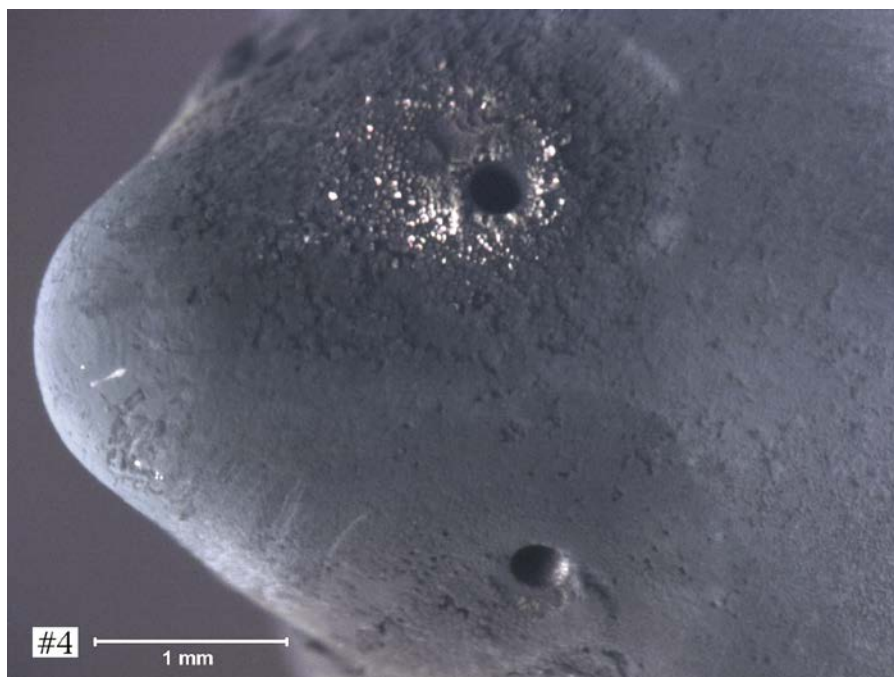**Figure B-15.  Post-Test Injector Tip, Injector 4**



**Figure B-16.  Post-Test Injector Tip, Injector 4 (Close)**